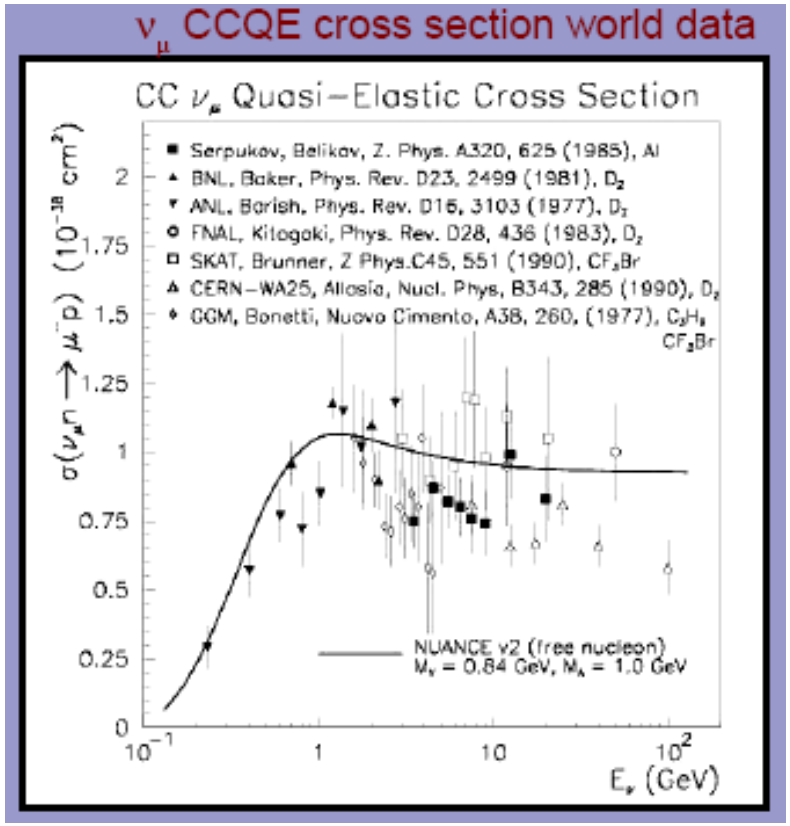
Lepton-Nucleus Cross Sections in MiniBooNE

(Neutrino Engineering…)

- This is really *two* talks…
  - MiniBooNE CCQE measurement
    - Work by Teppei Katori (University of Indiana)
      - (Thanks Teppei !!!)
    - Relevant to oscillation analysis
  - Possible future improvements to models
    - Detailed comparison to electron data to constrain nuclear response

MiniBooNE CCQE Measurement

- Charged Current Quasi Elastic (CCQE) reaction is the “golden” channel for the MiniBooNE oscillation analysis
- The event generator (Nuance) for our simulation employs a simple Fermi gas (FG) model for the nuclear response function (a la Smith and Moniz, 1972)
- We “tune” a few parameters of the simple FG model which is the subject of the first talk…



General cross section
(a la Simth and Moniz, 1972)

$$\left(\frac{d^2\sigma}{d\Omega_2 d\epsilon_2}\right)_{\nu/\bar{\nu}} = \frac{G_F^2 \cos^2\theta_c k_2^2 \cos^2(\frac{\chi}{2})}{2\pi^2 M_T}$$

Determined by
Electron scattering

$$\left\{ W_2 + \left[2W_1 + \frac{m_l^2}{M_T^2} W_\alpha \right] \tan^2(\frac{\chi}{2}) + \frac{(W_\beta \pm W_8)\, m_l^2}{M_T \epsilon_2 \cos^2(\frac{\chi}{2})} \right.$$

Small

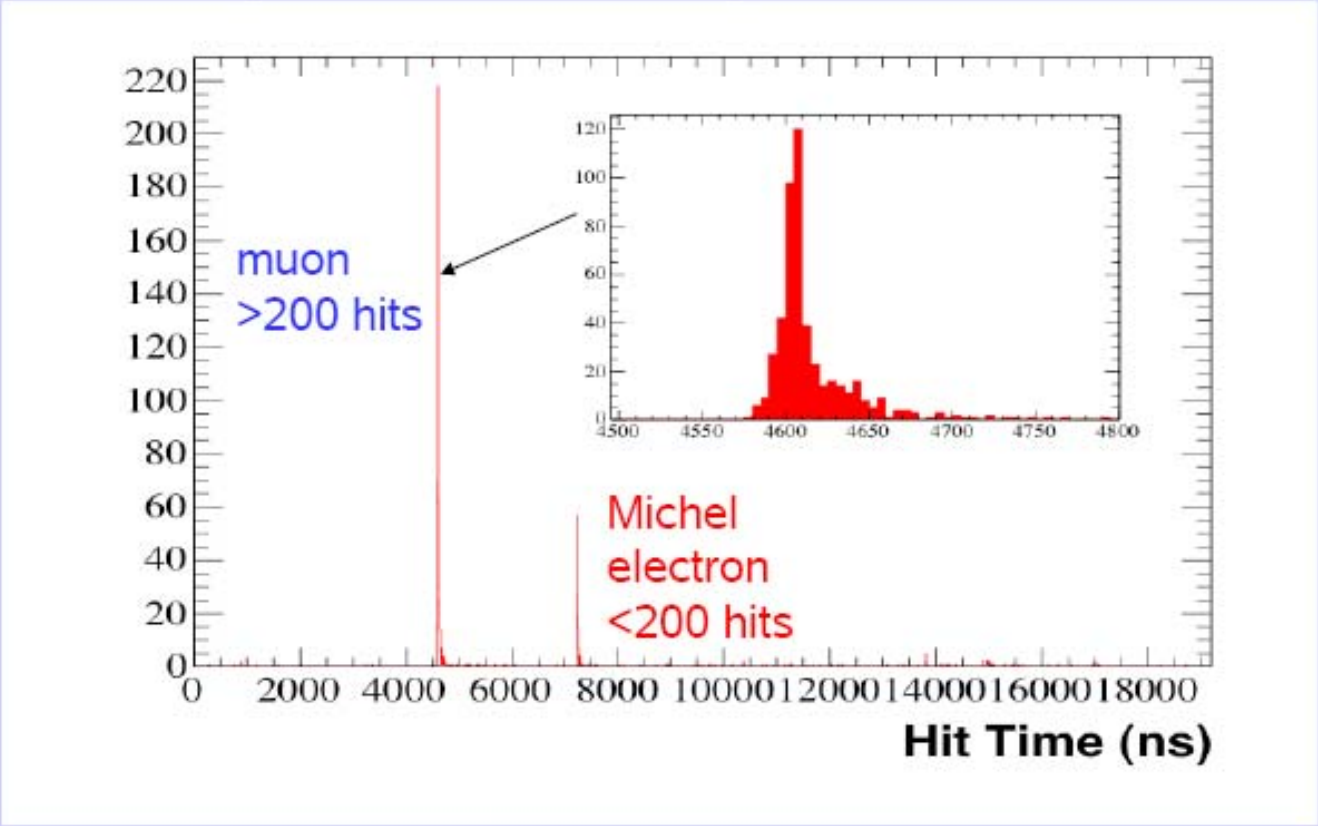
$$\left. \mp 2\left(\frac{W_8}{M_T}\right) \tan(\frac{\chi}{2}) \sec(\frac{\chi}{2}) \left[q^2 \cos^2(\frac{\chi}{2}) + |\mathbf{q}|^2 \sin^2(\frac{\chi}{2}) + m_l^2 \right]^{\frac{1}{2}} \right\}$$

W1, W2 are determined by electron scattering,
W8 must be determined by neutrino scattering

1. CCQE events in MiniBooNE

ν_μ CCQE interactions (ν+n $\rightarrow$ μ+p) has characteristic two "subevent" structure from muon decay

$$\nu_\mu + n \rightarrow \mu + p \qquad \mu \rightarrow \nu_\mu + \bar{\nu}_e + e$$



35.0% cut efficiency

197,308 events with 5.58E20POT

1. CCQE events in MiniBooNE

Cut and efficiency summary

total 2 subevents	54.2%
muon in beam window (4400ns < Time < 6400ns)	52.9%
muon veto hits < 6 and Michel electron veto hits < 6	46.4%
muon tank hits > 200 and Michel electron tank hits < 200	41.6%
fiducial reconstruction for muon	41.3%
muon and electron distance < 100cm	35.0%

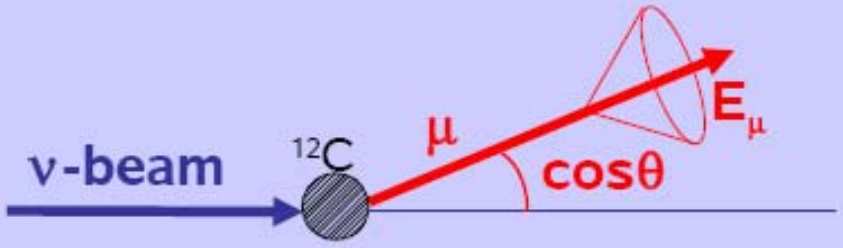
1. CCQE events in MiniBooNE

All kinematics are specified from 2 observables, muon energy E_μ and muon scattering angle θ

Energy of the neutrino E_ν and 4-momentum transfer Q^2 can be reconstructed by these 2 observables

$$E_\nu = \frac{2(M - E_B)E_\mu - (E_B^2 - 2ME_B + m_\mu^2 + \Delta M^2)}{2[(M - E_B) - E_\mu + p_\mu \cos\theta_\mu]}$$

$$Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - p_\mu \cos\theta_\mu)$$



2. Prediction for CCQE events

Smith and Moniz, Nucl.,Phys.,B43(1972)605

Relativistic Fermi Gas (RFG) Model

Carbon is described by the collection of incoherent Fermi gas particles.
All details come from hadronic tensor.

$$(W_{\mu\nu})_{ab} = \int_{Elo}^{Ehi} f(\vec{k}, \vec{q}, w) T_{\mu\nu} dE$$: hadronic tensor

$f(\vec{k}, \vec{q}, w)$: nucleon phase space density function

$T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P)$: nucleon tensor

$F_A(Q^2) = g_A/(1+Q^2/M_A^2)^2$: Axial form factor

Ehi : the highest energy state of nucleon $= \sqrt{(p_F^2 + M^2)}$

Elo : the lowest energy state of nucleon $= \sqrt{(p_F^2 + M^2)} - w + E_B$

3 parameters are especially important to control nuclear effect of Carbon;

M_A = 1.03GeV : axial mass

P_F = 220MeV : Fermi momentum

E_B = 34MeV : binding energy

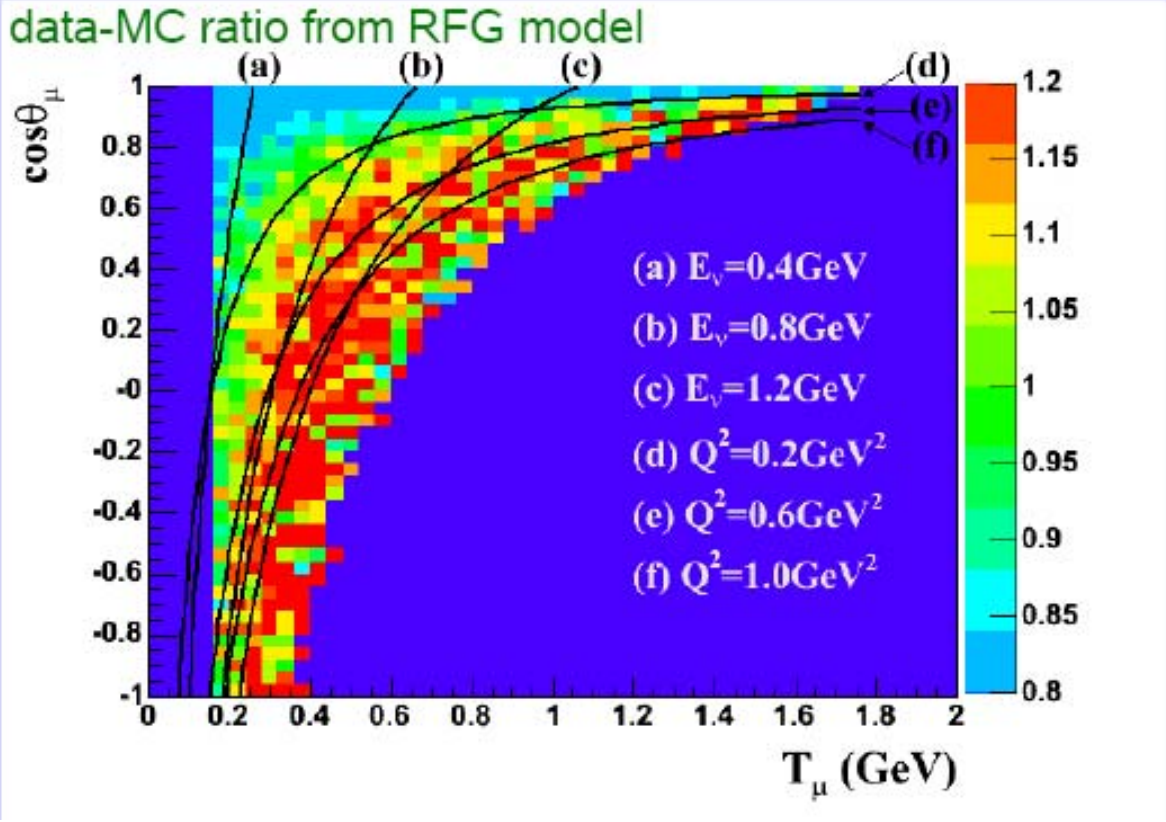
3. CCQE data-MC comparison

CCQE kinematics phase space

The data-MC agreement is not great

Since data-MC disagreements align on the Q^2 lines, not $E\nu$ lines, the source of data-MC disagreement is not the neutrino beam prediction, but the neutrino cross section prediction.

(this is an assumption…)

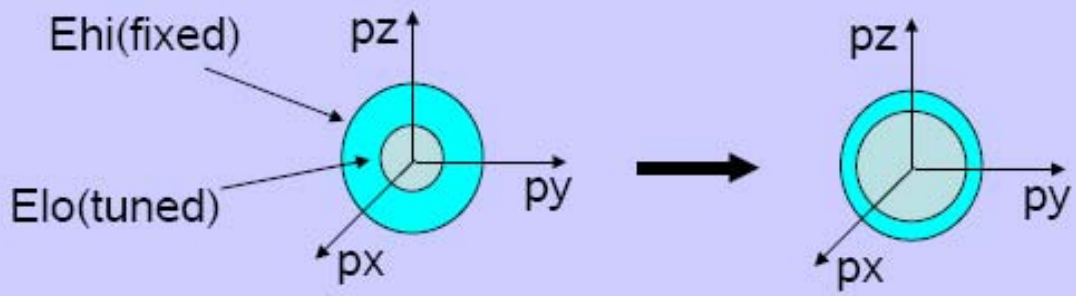


3. CCQE data-MC comparison

Pauli blocking parameter "kappa" : κ

To enhance the Pauli blocking at low Q^2, we introduced a new parameter κ, which is the scale factor of lower bound of nucleon sea and controls the size of nucleon phase space

$$\mathrm{Elo} = \boxed{\kappa}\left(\sqrt{(p_F^2 + M^2)} - w + E_B\right)$$



This modification gives significant effect only at low Q^2 region

We tune the nuclear parameters in RFG model using Q^2 distribution;

M_A = tuned

P_F = fixed

E_B = fixed

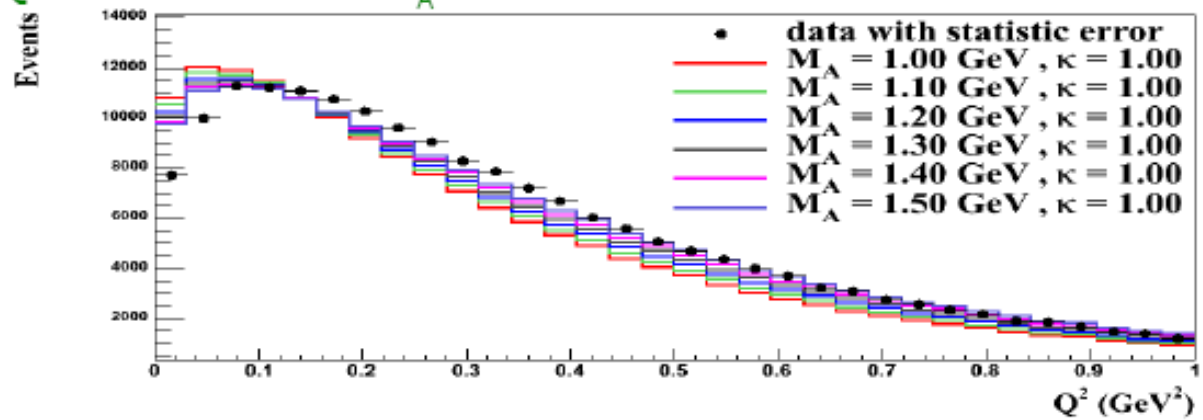
κ = tuned

3. CCQE data-MC comparison

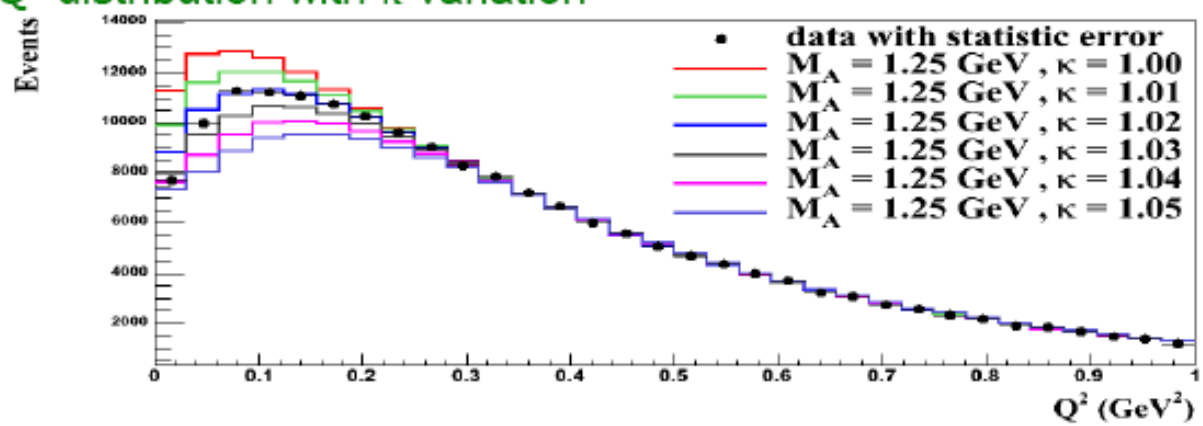
M_A and κ are simultaneously fit to the data

2% change of κ is sufficient to take account the data deficit at low Q^2 region

Q^2 distribution with M_A variation



Q^2 distribution with κ variation



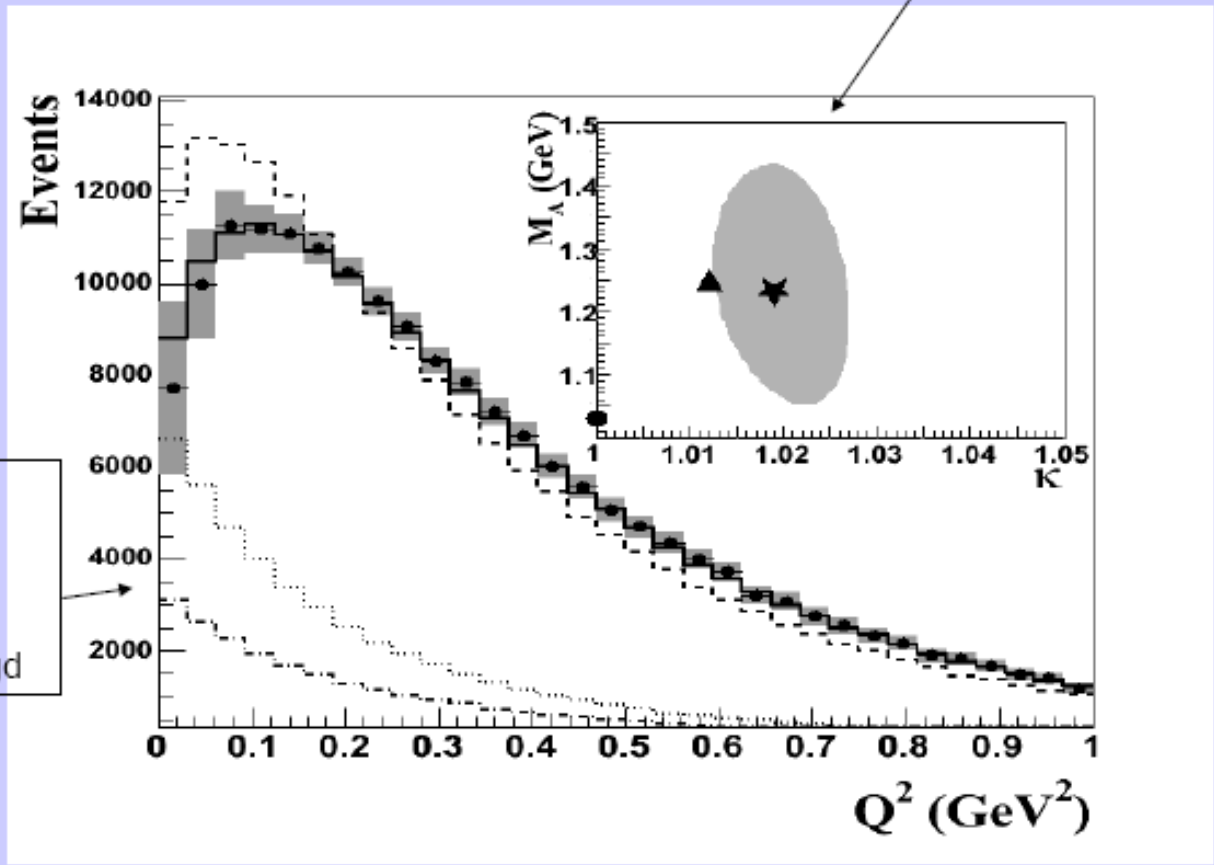
4. Fit results

M_A - κ fit result

M_A = 1.23 ± 0.20(stat+sys)

κ = 1.019 ± 0.011(stat+sys)

circle: before fit
star: after fit with 1-sigma contour
triangle: bkgd shape uncertainty



dots : data with error bar
dashed line : before fit
solid line : after fit
dotted line : background
dash-dotted :non-CCQElike bkgd

4. Fit results

M_A - κ fit result

$M_A = 1.23 \pm 0.20$(stat+sys)

$\kappa = 1.019 \pm 0.011$(stat+sys)

Although fit is done in Q^2 distribution, entire CCQE kinematics is improved

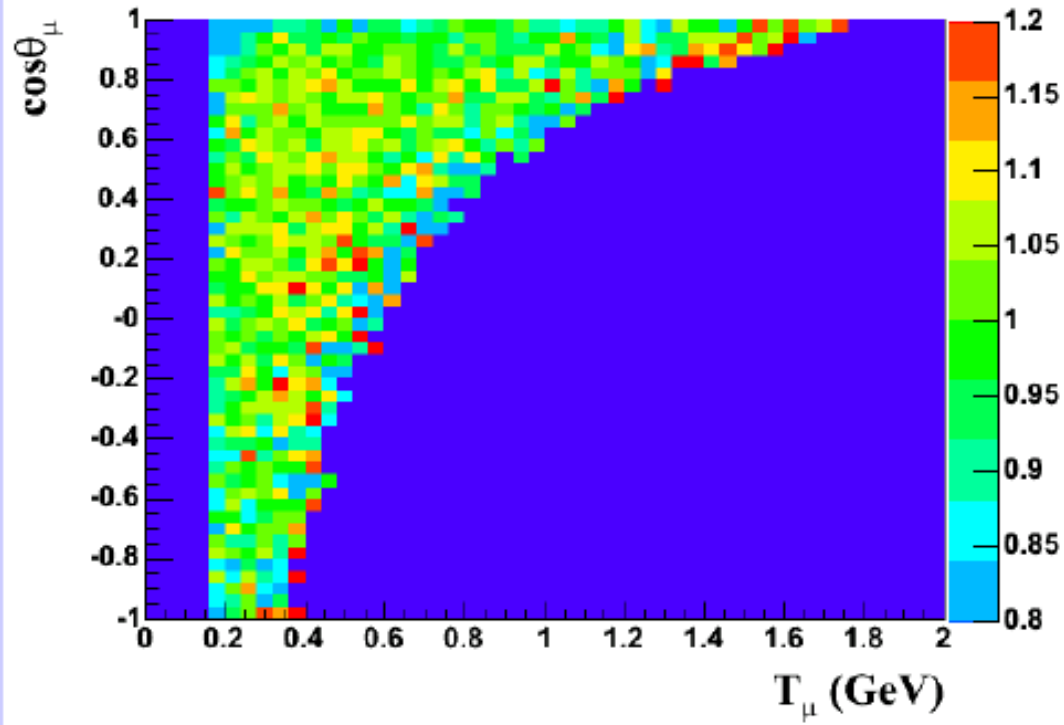
before

χ^2/dof = 79.5/53, P(χ^2) = 1%

after

χ^2/dof = 45.1/53, P(χ^2) = 77%

data-MC ratio after the fit



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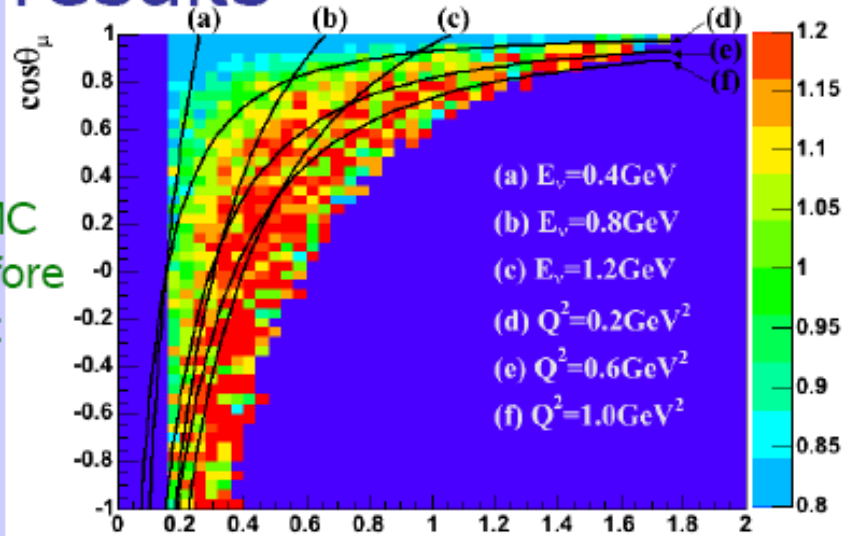
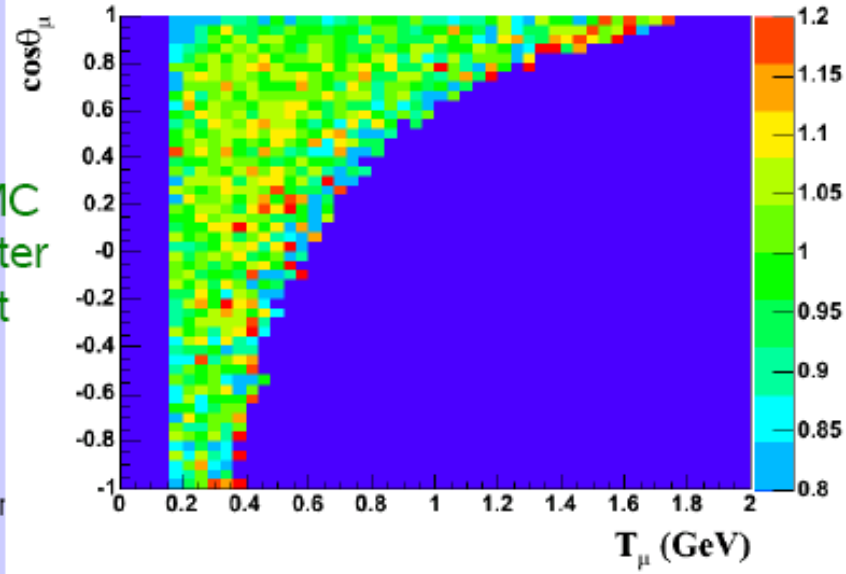


data-MC ratio after the fit

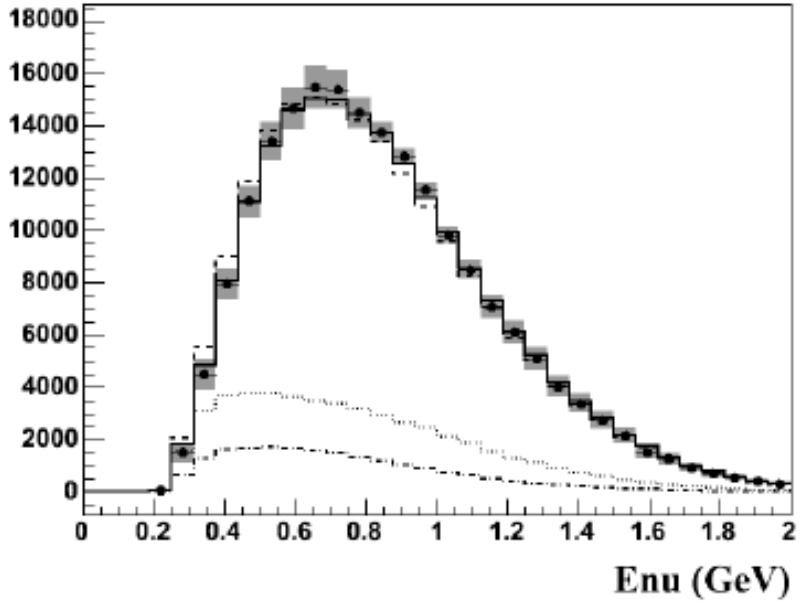


4. Fit results

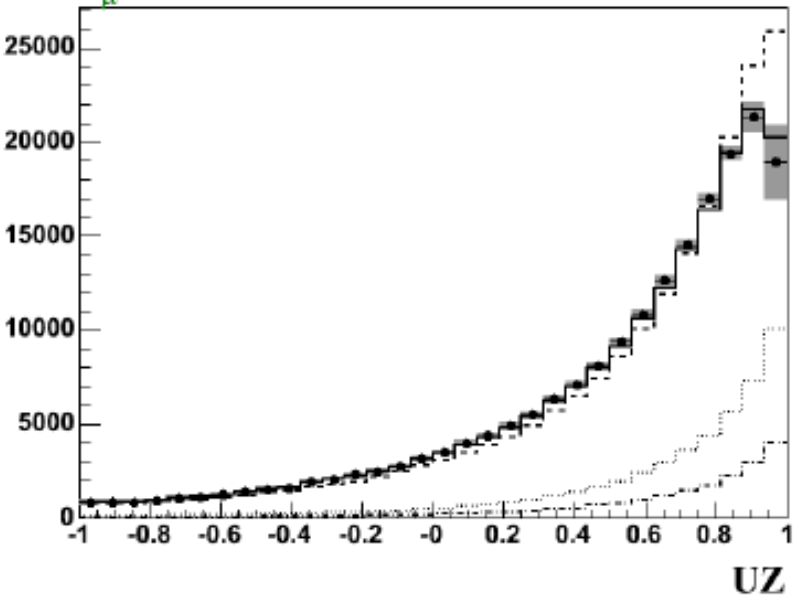
Other kinematics distribution also show very good data-MC agreement
(This is critical for MiniBooNE neutrino oscillation search experiment)

MiniBooNE collaboration,
arXiv:0704.1500 [hep-ex] (2007)

Eν distribution



$\cos\theta_\mu$ distribution



4. Fit results

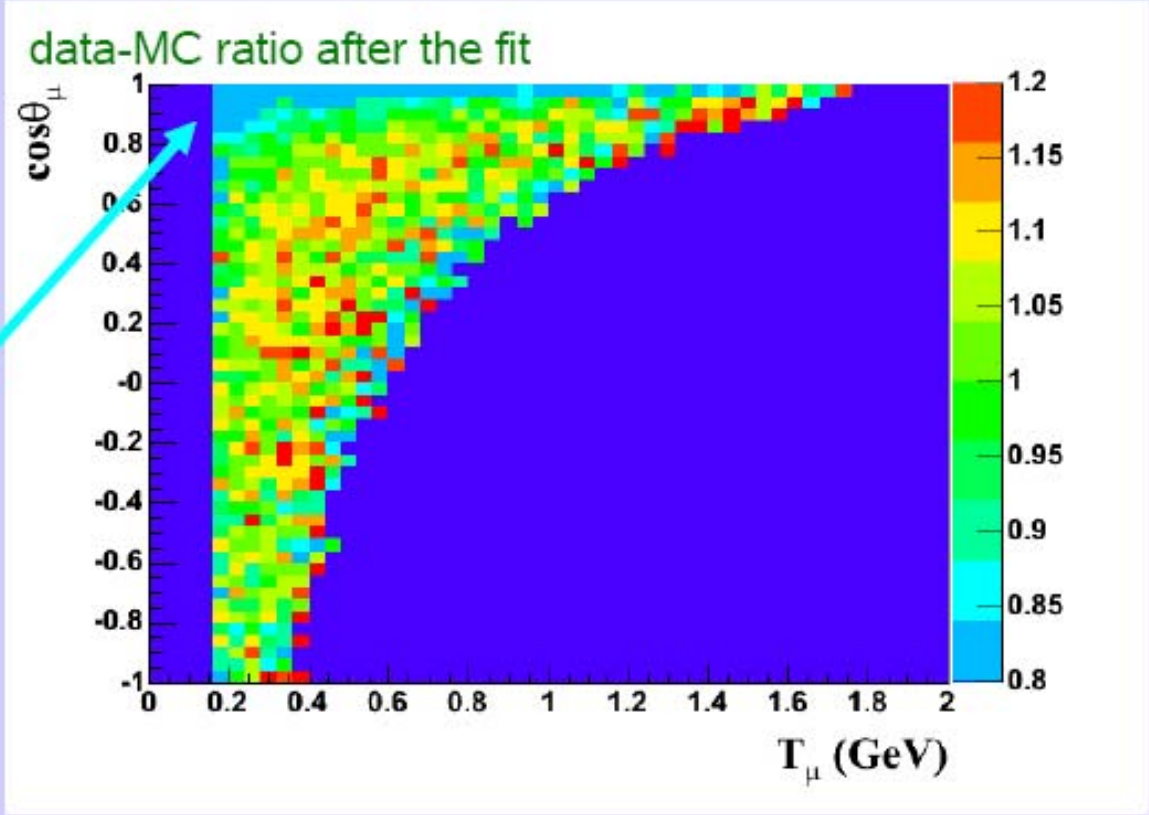
M_A only fit result

M_A = 1.25 ± 0.12(stat+sys)

fit with fixing κ for $0.25<Q^2(GeV^2)<1.0$

good agreement above $0.25GeV^2$ but gross disagreement at low Q^2 region

This fit cannot improve entire CCQE phase space



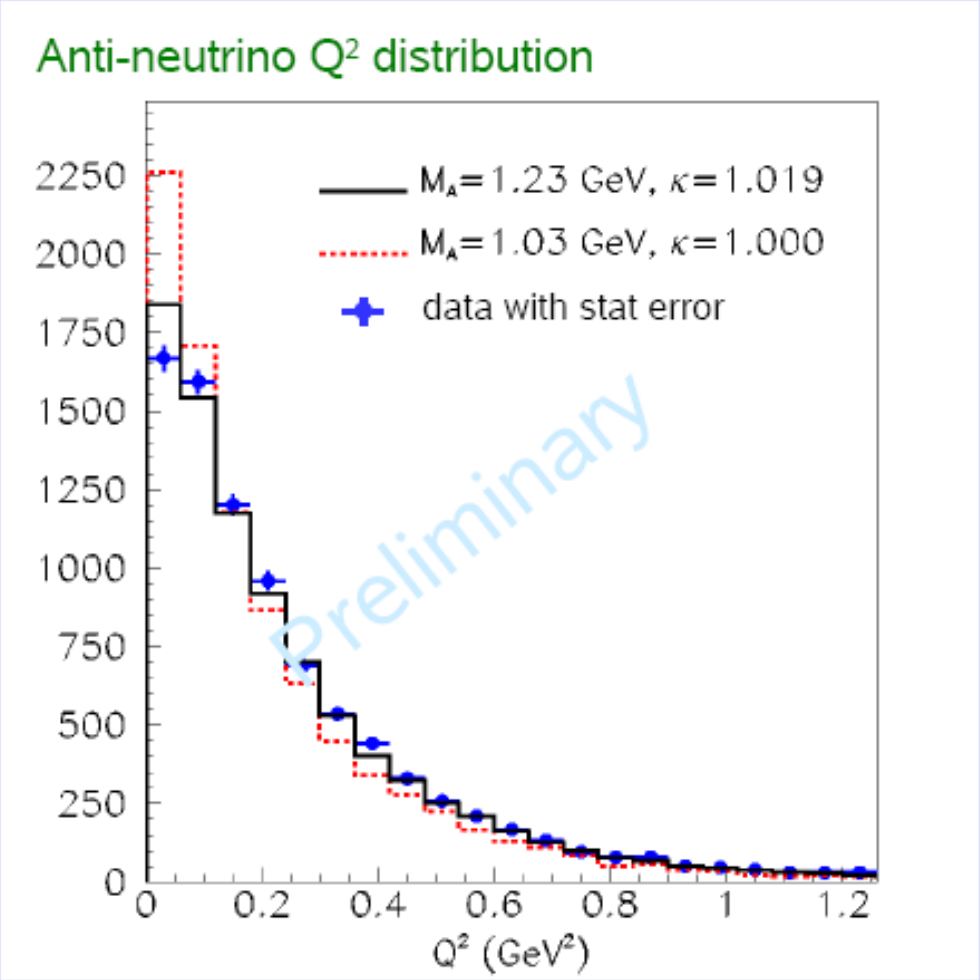
5. Anti-neutrino CCQE events

Anti-neutrino Q^2 distribution

MiniBooNE anti-neutrino CCQE
8772 events
(1651 total for pre-MiniBooNE data)

We use same cut with neutrino mode

The values of M_A and κ extracted from neutrino mode are employed to anti-neutrino MC, and they describe data Q^2 distribution well.



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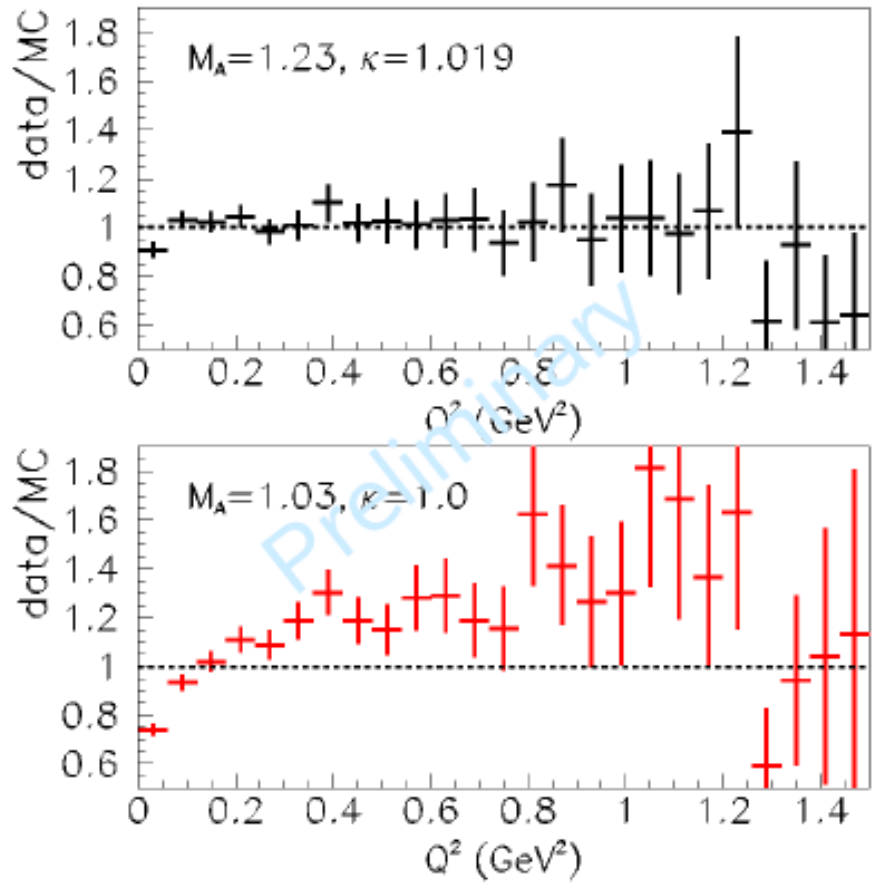
Anti-neutrino Q^2 distribution data-MC ratio



5. Anti-neutrino CCQE events

Anti-neutrino CCQE kinematics

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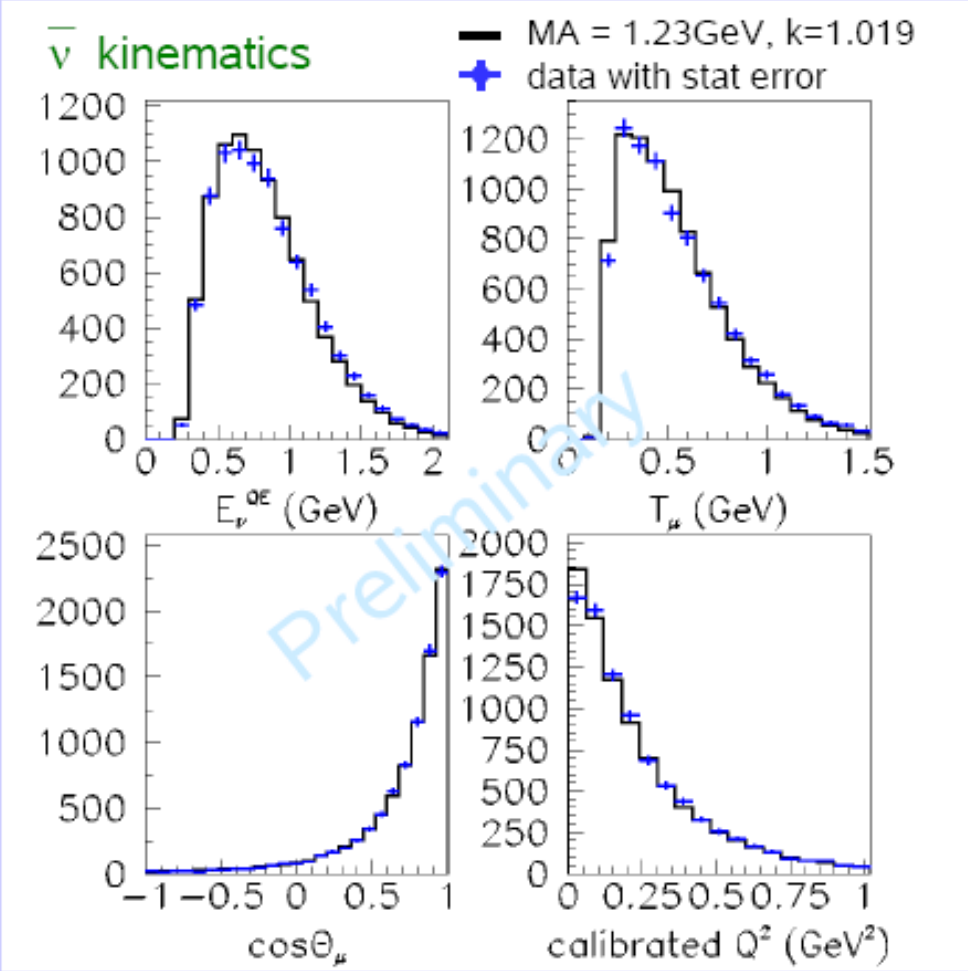
The values of M_A and κ extracted from neutrino mode are employed to anti-neutrino MC, and they describe data Q^2 distribution well.

Anti-neutrino CCQE kinematics variables are described by the MC well, too.



Lepton-Nucleus Cross Sections in the Energy Range 150-700 MeV

Motivation
Nuclear Models
Effects of Nuclear Correlations
Benchmark Data: C(e,e')X Saclay ALS
Comparison: Theory and Experiment
Extensions to Neutrino Scattering
Summary

Geoffrey Mills
July 2, 2007

Motivation

- A simple truth in neutrino physics:

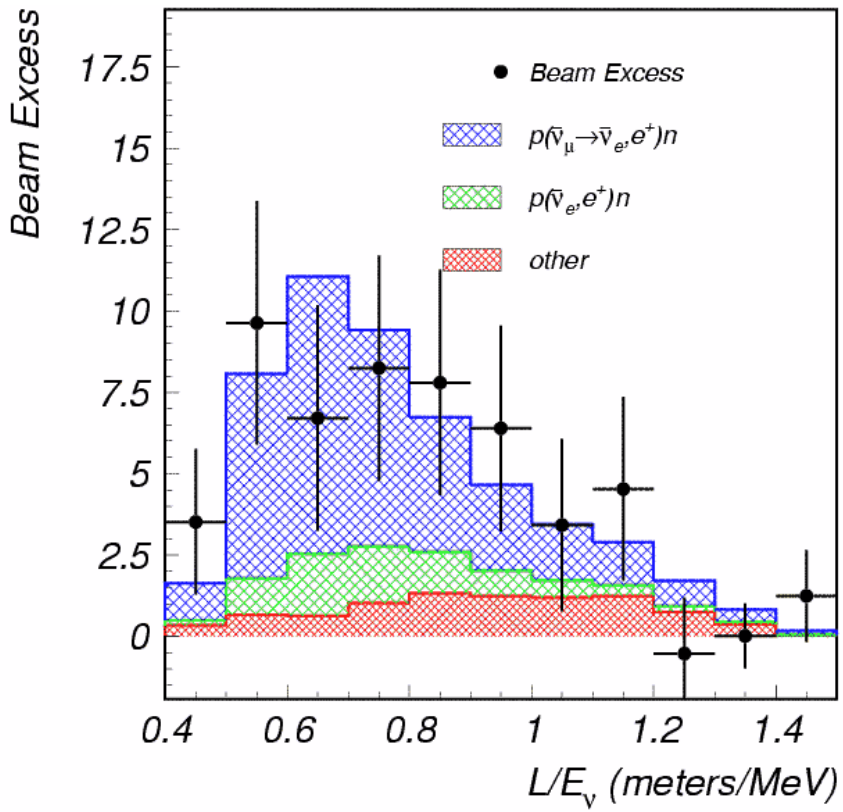
Contains everything interesting: oscillation physics, exotic event rates, cross sections, etc.

$$\left(\text{observed event rate}\right) = \left(\text{cross section}\right)\left(\text{flux of neutrinos}\right)\left(\text{detection efficiency}\right)$$

The subject of this talk

MiniBooNE Neutrino Cross Section Predictions

- MiniBooNE was designed to utilize the quasi elastic neutrino-^{12}C charged current reaction to study neutrino oscillations.
- The L/E of the LSND result was centered in L/E around 0.5-1.4 meter/MeV.
- This corresponds to neutrino energies in the range 350 MeV to 1000 MeV at the MiniBooNE distance of 500 meters.



A “first principle” calculation is too difficult

- In systems of A >~ 10 nucleons it is not (yet) possible to perform exact, many-body, field theory calculations. MiniBooNE uses Carbon, A=12… oh well…

- There are several different approaches commonly seen: shell model, TDA, RPA, shell model, etc…

- Here, I employ a simple “Fermi Gas motivated” momentum-space spectral function description, which seems to work remarkably (better than it should!). It can be corrected for nuclear effects and extended to higher energies.

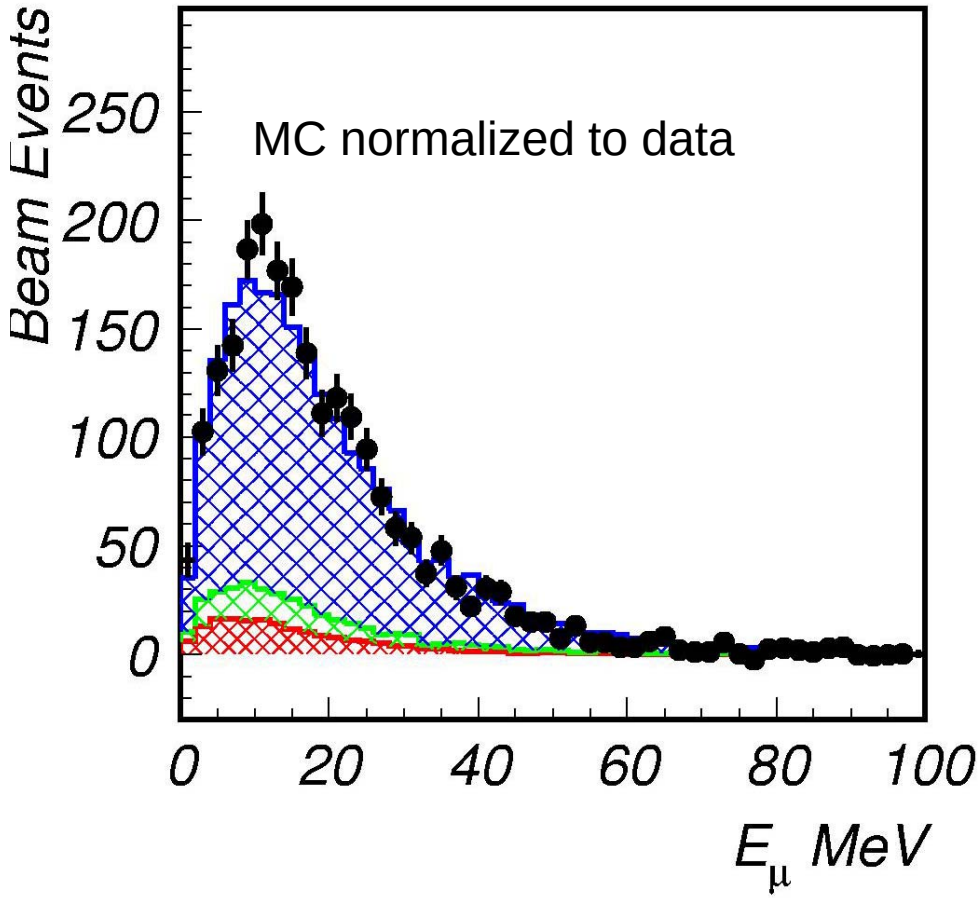
LSND Excited State ν_μ-^{12}C Events

- The only "precision" measurement of quasi elastic neutrino scattering on Carbon

$$\nu_\mu {}^{12}C \rightarrow \mu^- {}^{12}N^*$$

$$\langle \sigma \rangle_{meas} = (10.5 \pm 1.6) \times 10^{-40} cm^2$$

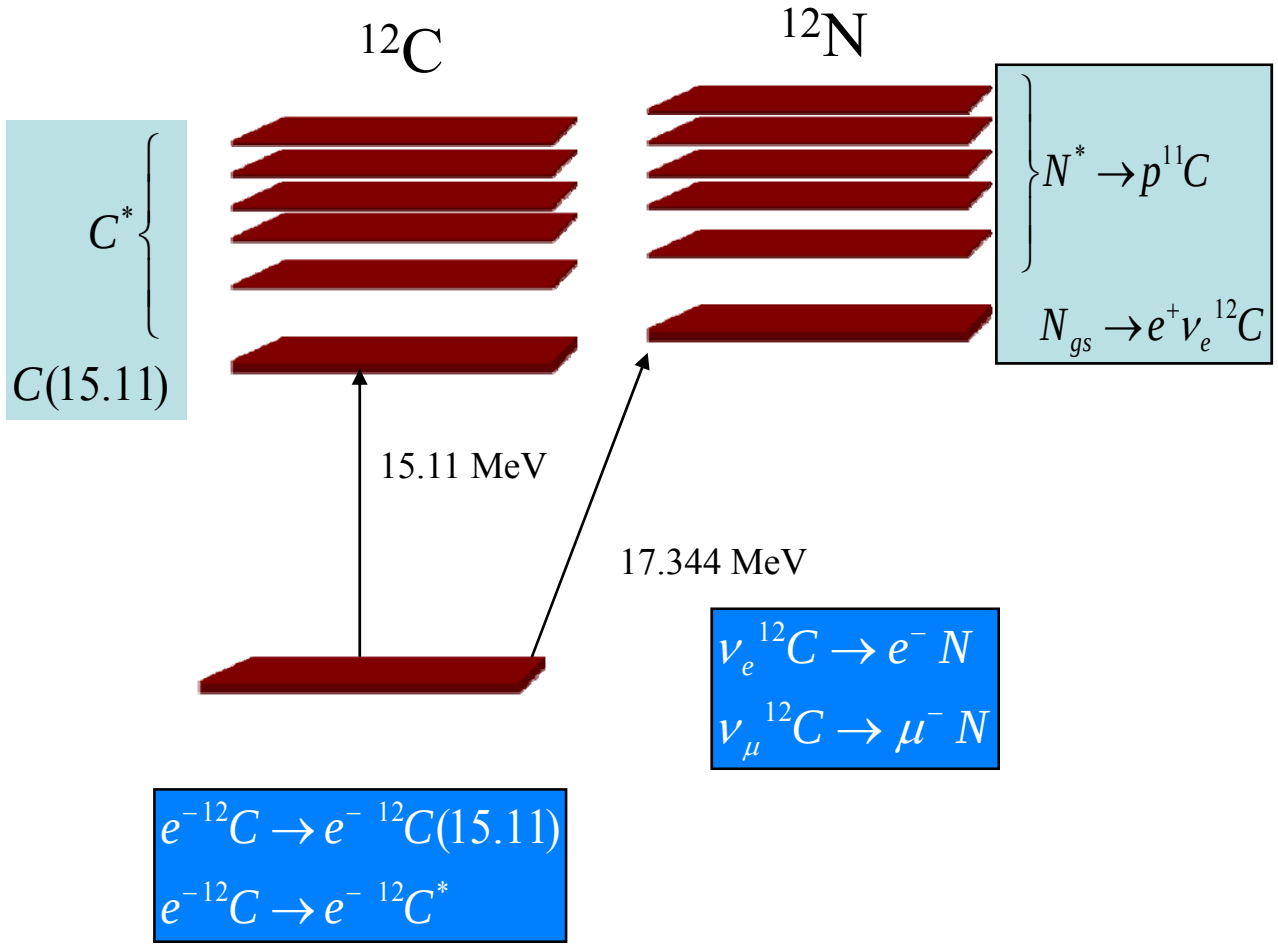
This is 40-50% lower than expected!



Neutrino and Electron Scattering on ^{12}C

Time Tested Strategy:

Use electron scattering to measure the response of the nucleus.



Moments of Initial Nucleon Momenta

$$f(\mathbf{k},\mathbf{q},\omega) = \frac{M_T\Omega}{(2\pi)^3}\frac{\delta(\omega+\epsilon_{\mathbf{k}}+U(|\mathbf{k}|)-\epsilon_{|\mathbf{k}-\mathbf{q}|}-U(|\mathbf{k}-\mathbf{q}|))n_i(\mathbf{k})(1-n_f(|\mathbf{k}-\mathbf{q}|))}{\epsilon_{\mathbf{k}}\epsilon_{|\mathbf{k}-\mathbf{q}|}}$$

Electron scattering:

$$\{a_1,\ldots,a_5\} = \int d^3k f(\mathbf{k},\mathbf{q},\omega)\{1,\frac{|\mathbf{k}|^2}{M^2},\frac{|\mathbf{k}|^2 cos^2\tau}{M^2},\frac{\epsilon_{\mathbf{k}}^2}{M_2},\frac{\epsilon_{\mathbf{k}}|\mathbf{k}|cos\tau}{M^2}\}$$

Neutrino scattering:

$$a_{\{1,\ldots,7\}}(|\mathbf{q}|^2,\omega) = \int d^3k f(\mathbf{k},\mathbf{q},\omega)\{1,\frac{|\mathbf{k}|^2}{M^2},\frac{|\mathbf{k}|^2 cos^2\tau}{M^2},\frac{\epsilon_{\mathbf{k}}^2}{M^2},\frac{\epsilon_{\mathbf{k}}|\mathbf{k}|cos\tau}{M^2},\frac{|\mathbf{k}|cos\tau}{M},\frac{\epsilon_{\mathbf{k}}}{M}\}$$

Some Important Nuclear Effects

- **Finite system effects**
  - **There are only 12 nucleons in carbon**
  - **Start with harmonic oscillator ground state momentum distributions**

- **Non-local nuclear potential**
  - **Also known as long range correlations**
  - **Due to strongly attractive scalar field (σ)**
  - **Implies a dispersion relation for the nucleon**

- **Short range correlations**
  - **Due to the nucleon's hard core, i.e. repulsive vector forces (ω)**
  - **Causes high momentum tails to nucleon momentum distributions**

Finite System with A=12

- **Use a harmonic oscillator momentum distribution as a starting point**

$$n(k) = \left(1 + \frac{3}{4}\left(\frac{k}{k_0}\right)^2\right) e^{-\left(\frac{k}{k_0}\right)^2}$$

k_0 controls the oscillator strength ~ 122 MeV/c

Long Range Correlations

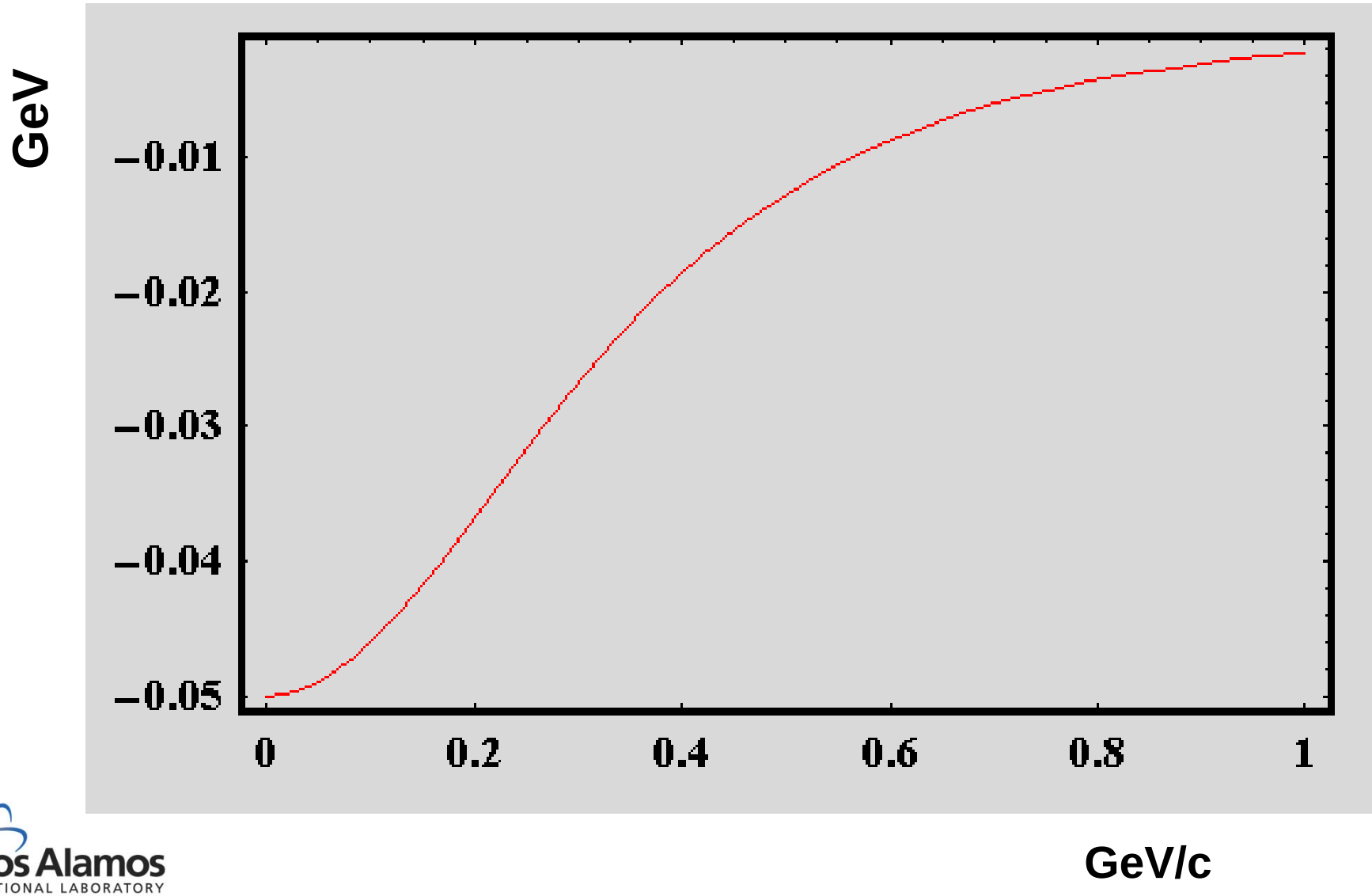
Non-local nuclear potential form:
(M is the nucleon mass, k is the nucleon momentum)

$$U(|\mathbf{k}|) = U_0\left(1 - a\left(\frac{k}{M}\right)^2 - b\left(\frac{k}{M}\right)^4 + \cdots\right) \approx \frac{U_0}{\left(1 + a\left(\frac{k}{M}\right)^2 + b\left(\frac{k}{M}\right)^4\right)}$$

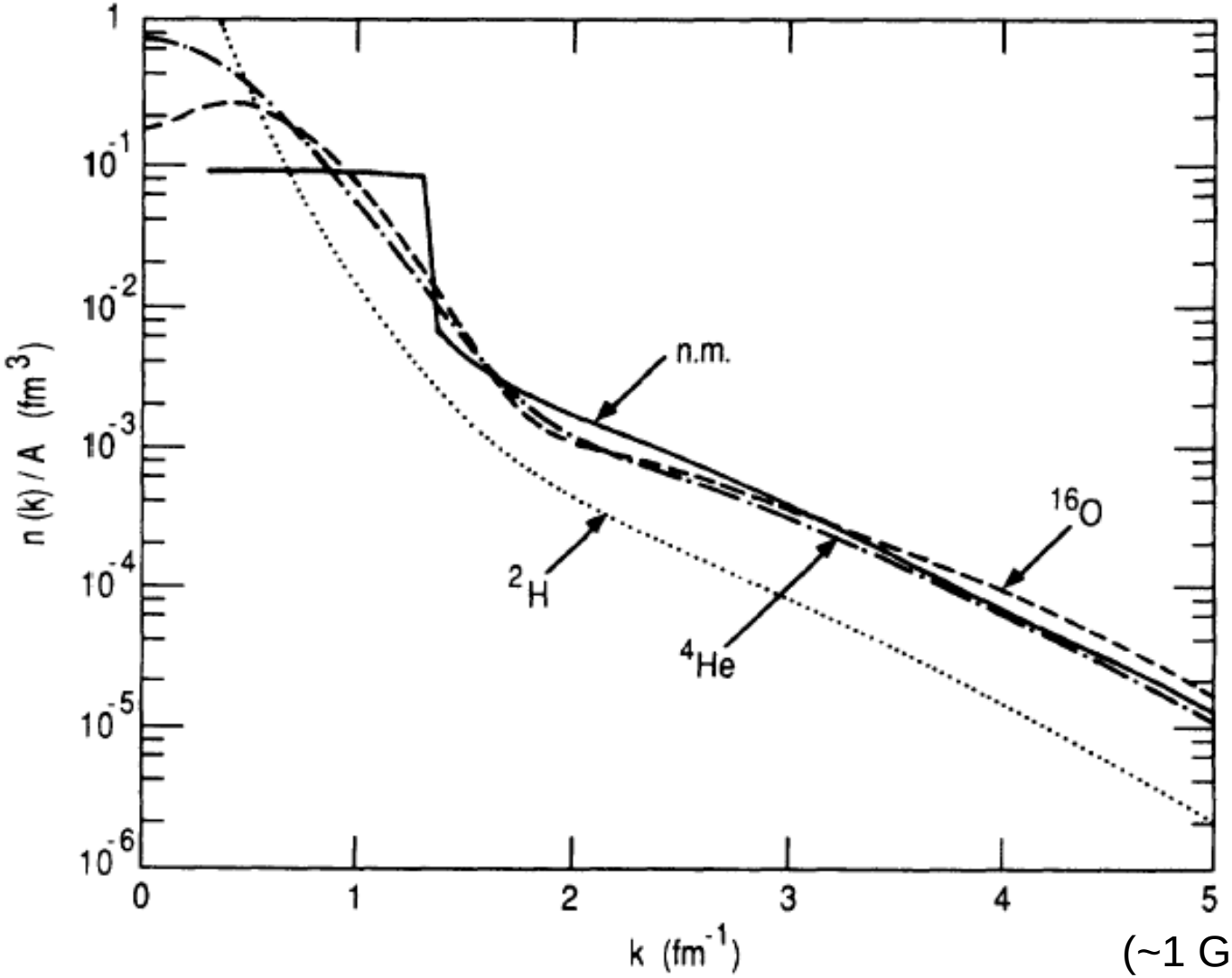
This fractional form has nice properties:

- **approximates a scalar interaction (σ field)**
- **gives correct dispersive behavior at low k**
- **goes to zero at high momentum**
- **a ~ 7.9, b~10, M is nucleon mass**

U(k)



Effects of Short Range Correlations



(~1 GeV/c)

Pandharipande et. al., Phys Rev C 46, 1741 (1992) , fig 4

Short Range Correlations cont.

- Dominant effect is high momentum tail in n(k)

$$n(k) = (1 - f_{tail})\, n_{ho}(k) + f_{tail}\; n_{tail}(k)$$

$$n(k) = \left(1 + \frac{3}{4}\left(\frac{k}{k_0}\right)^2\right) e^{-\left(\frac{k}{k_0}\right)^2}$$

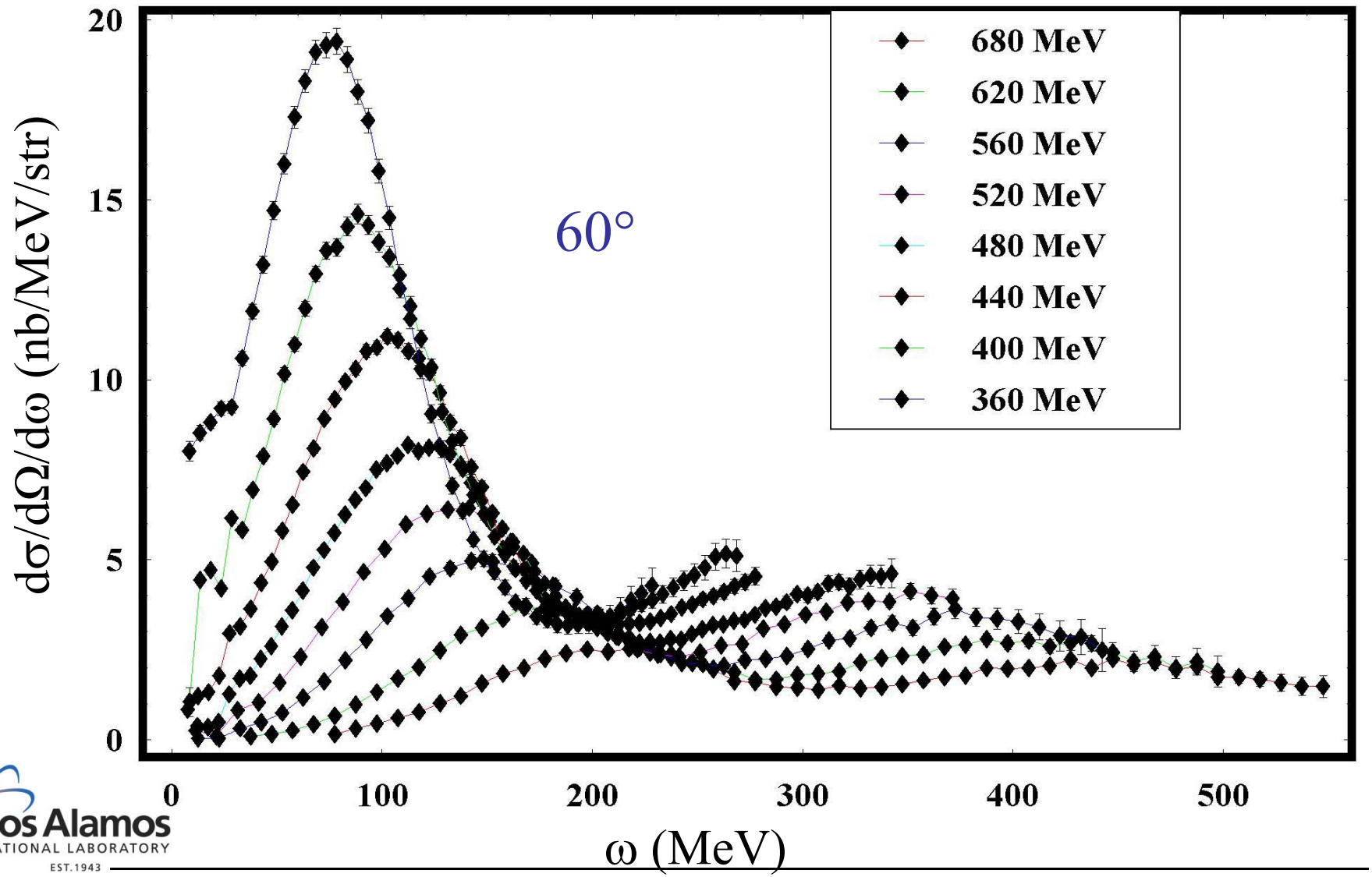
$$n_{tail}(k) = \frac{N_{tail}}{1 + \left(\frac{k}{k_{tail}}\right)^4}.$$

- k_{tail}~350 MeV/c, f_{tail}~0.30, N_{tail} normalization

Note: It is vital to include the recoil energy in the integration over k

Our Benchmark: ALS (Saclay) Data

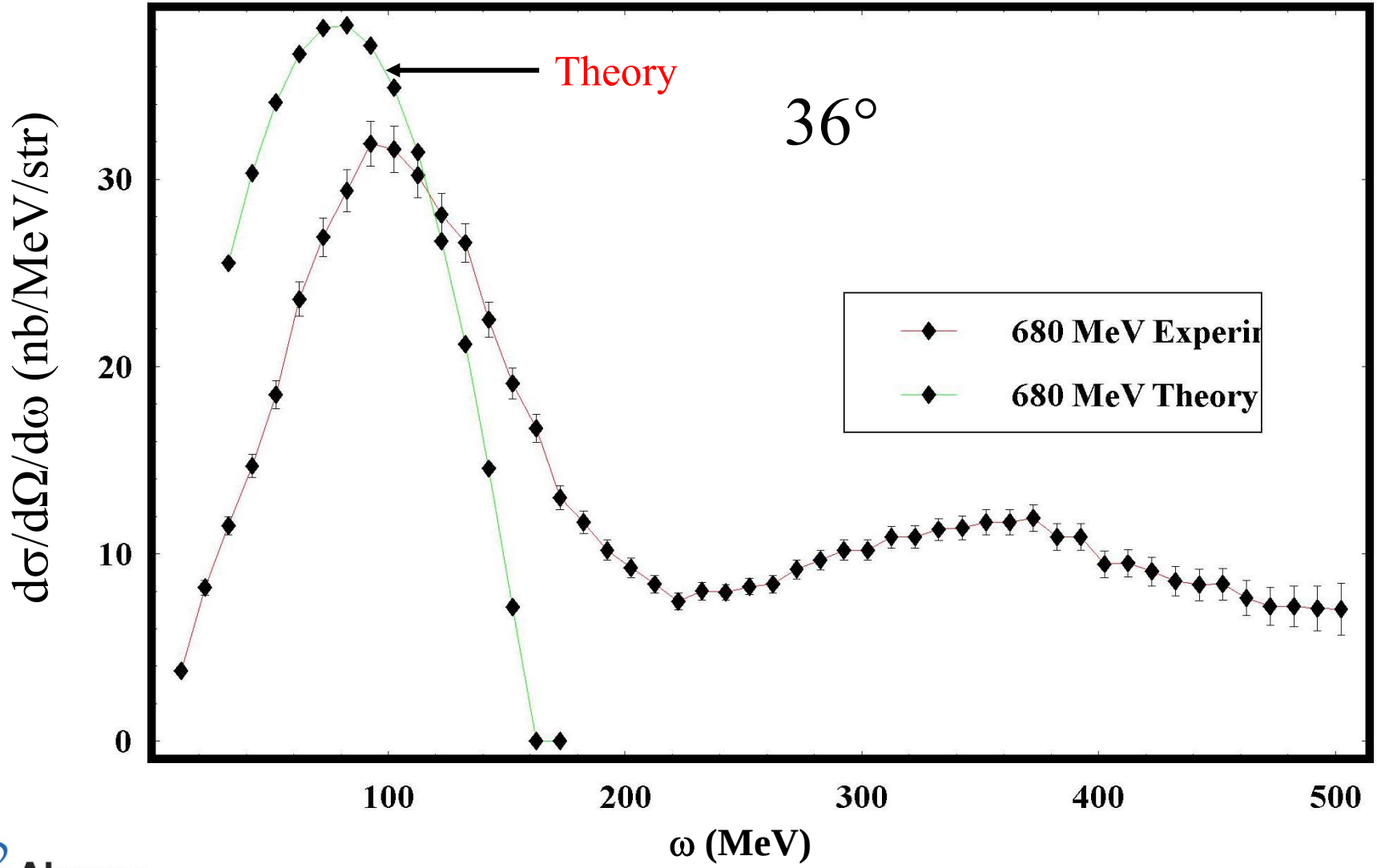
Electron energies 150 MeV->680 MeV



Model 0 (naive)

- Simple Fermi Gas (sphere)
- No binding energy
- No nuclear potential effects
- Impulse approximation

Model 0 (naive)



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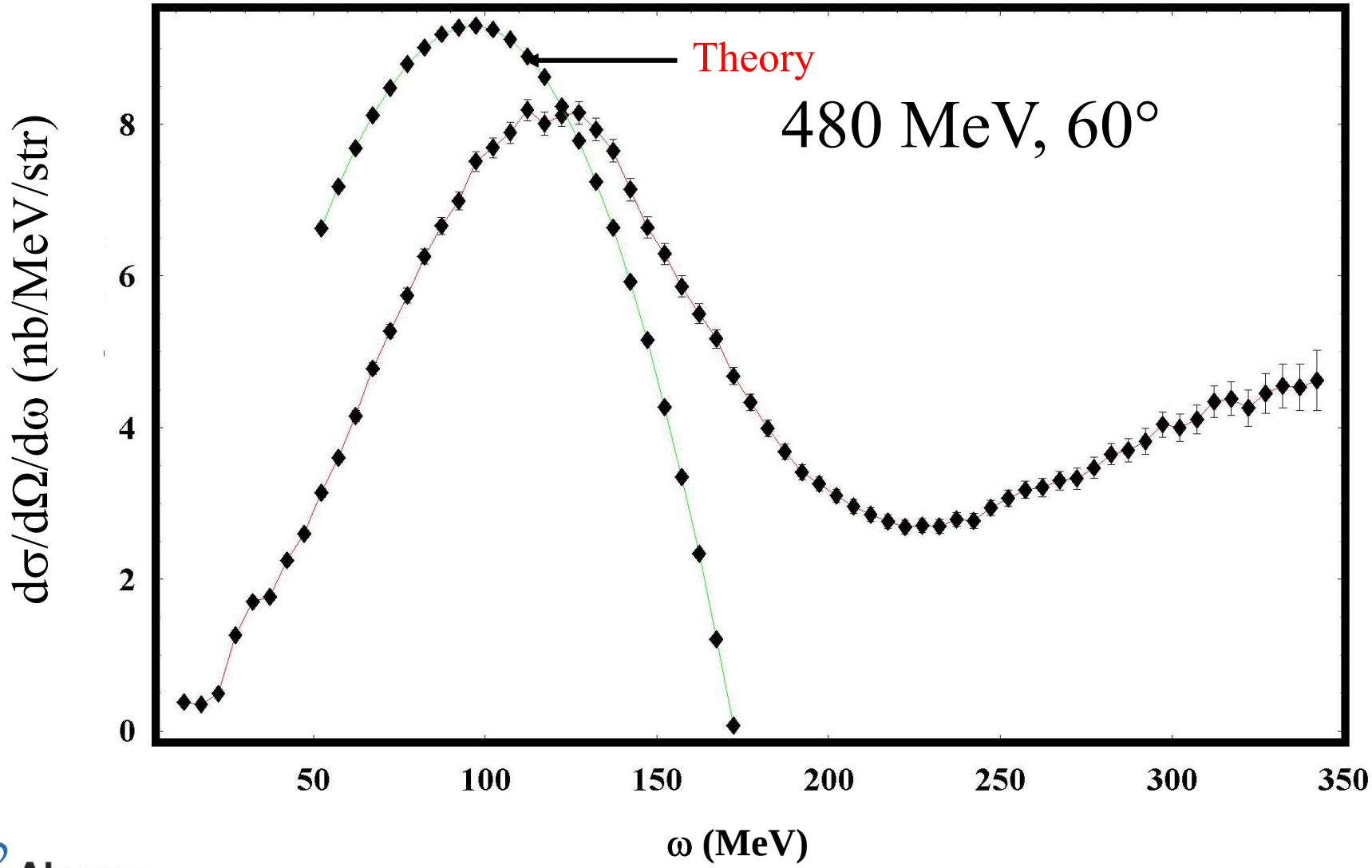

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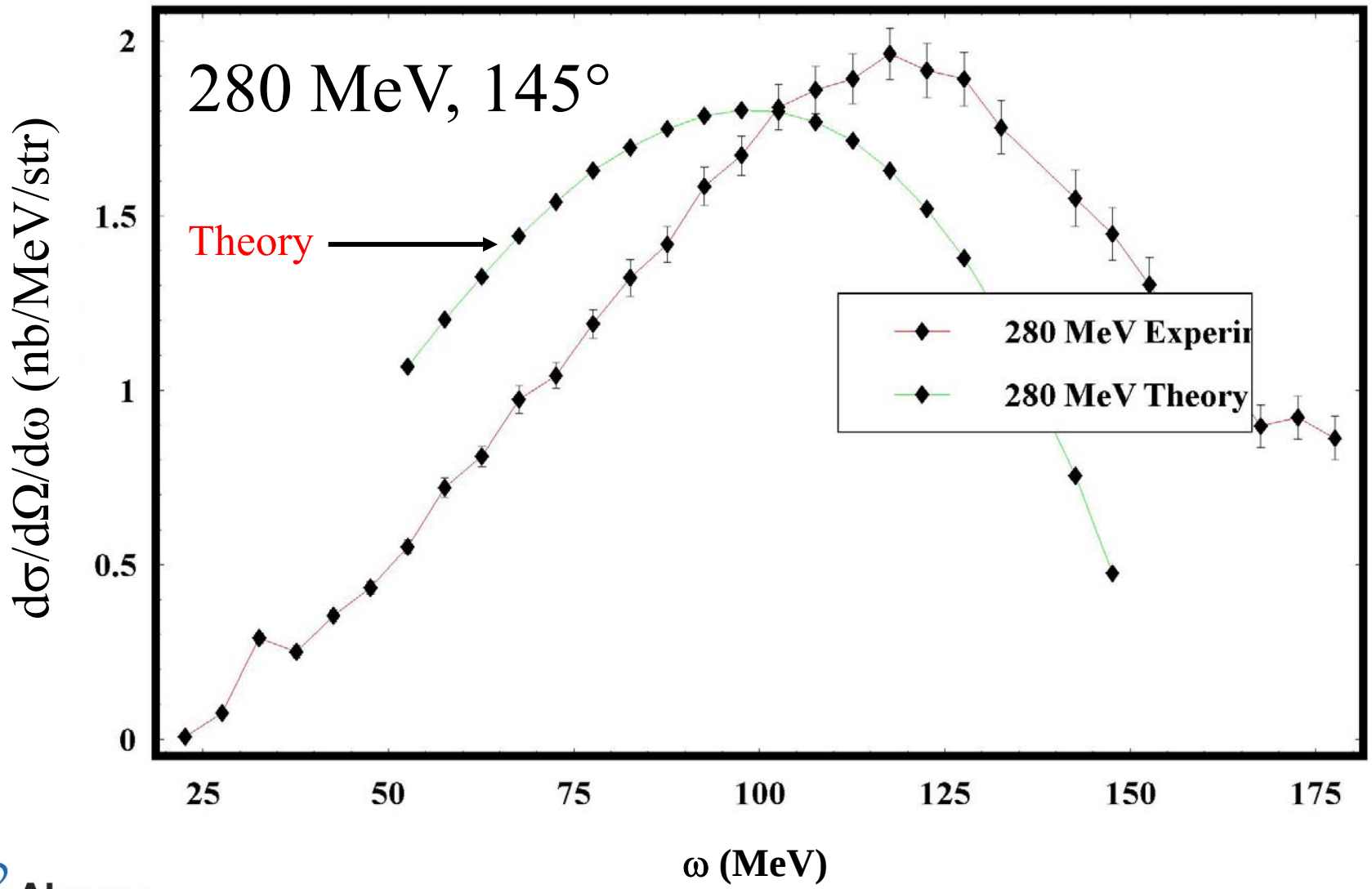
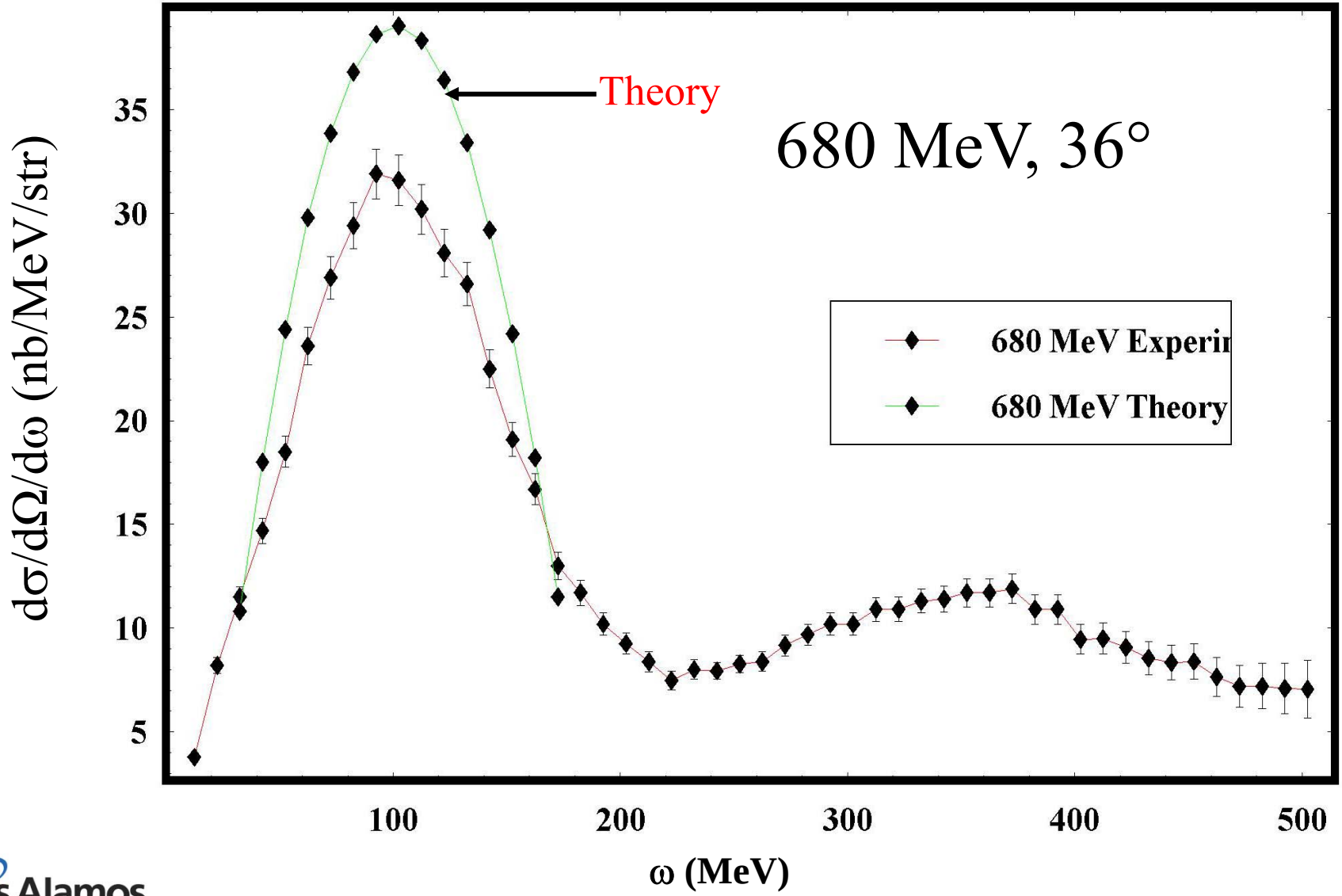


Model 1

- Simple Fermi Gas (sphere)
- Include binding energy
- No nuclear potential
- Impulse approximation

Model 1 (better)



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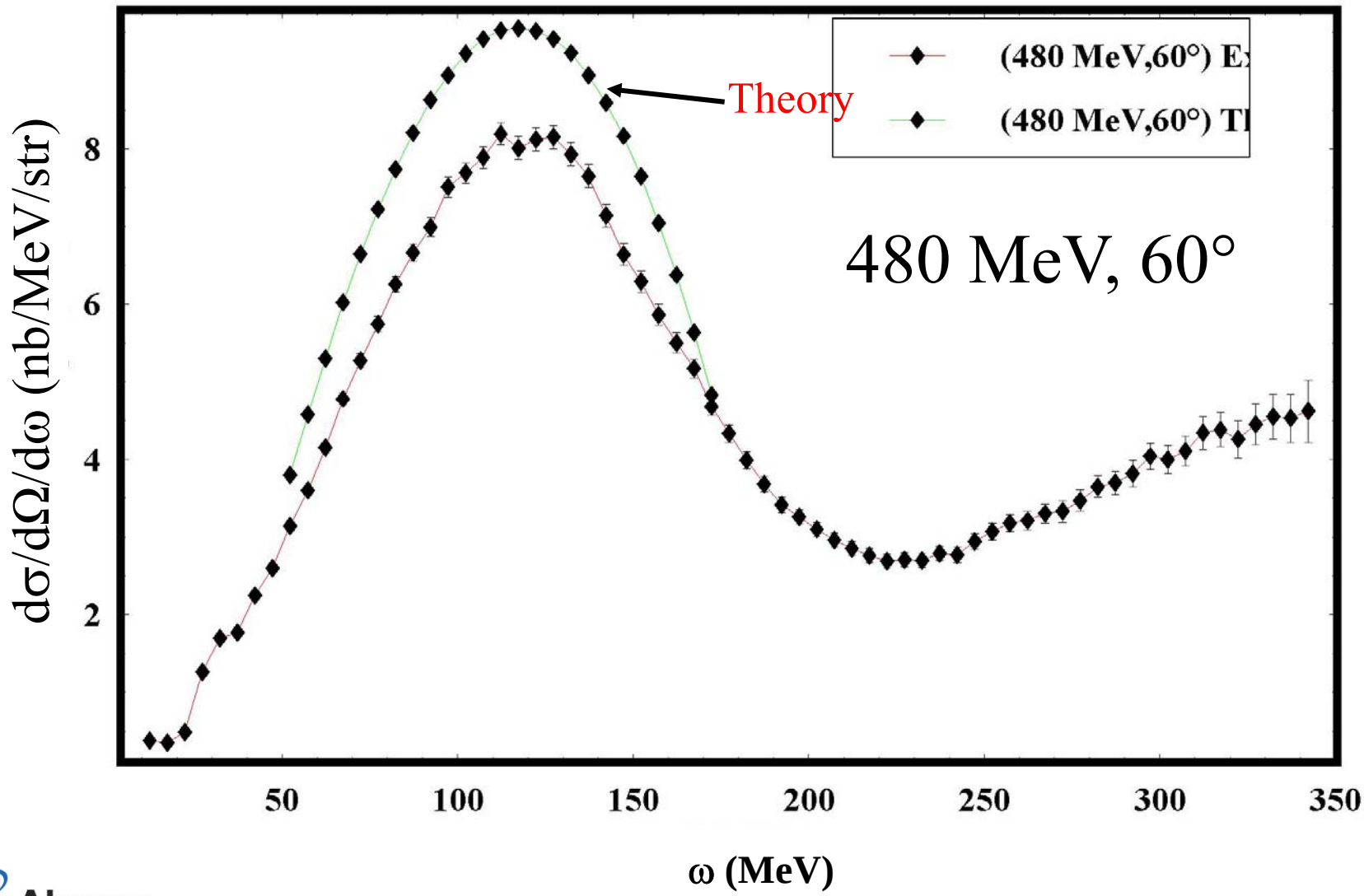
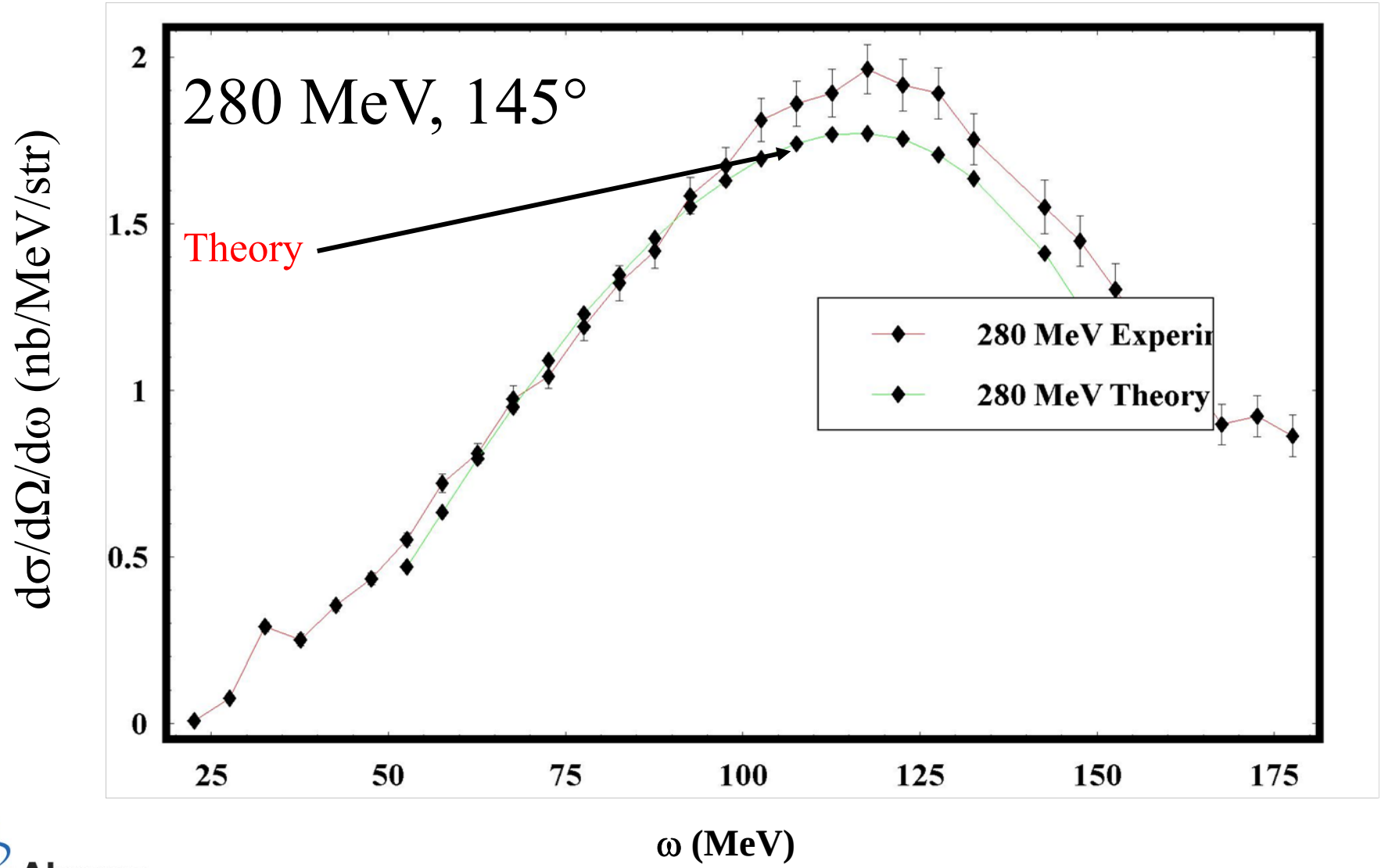


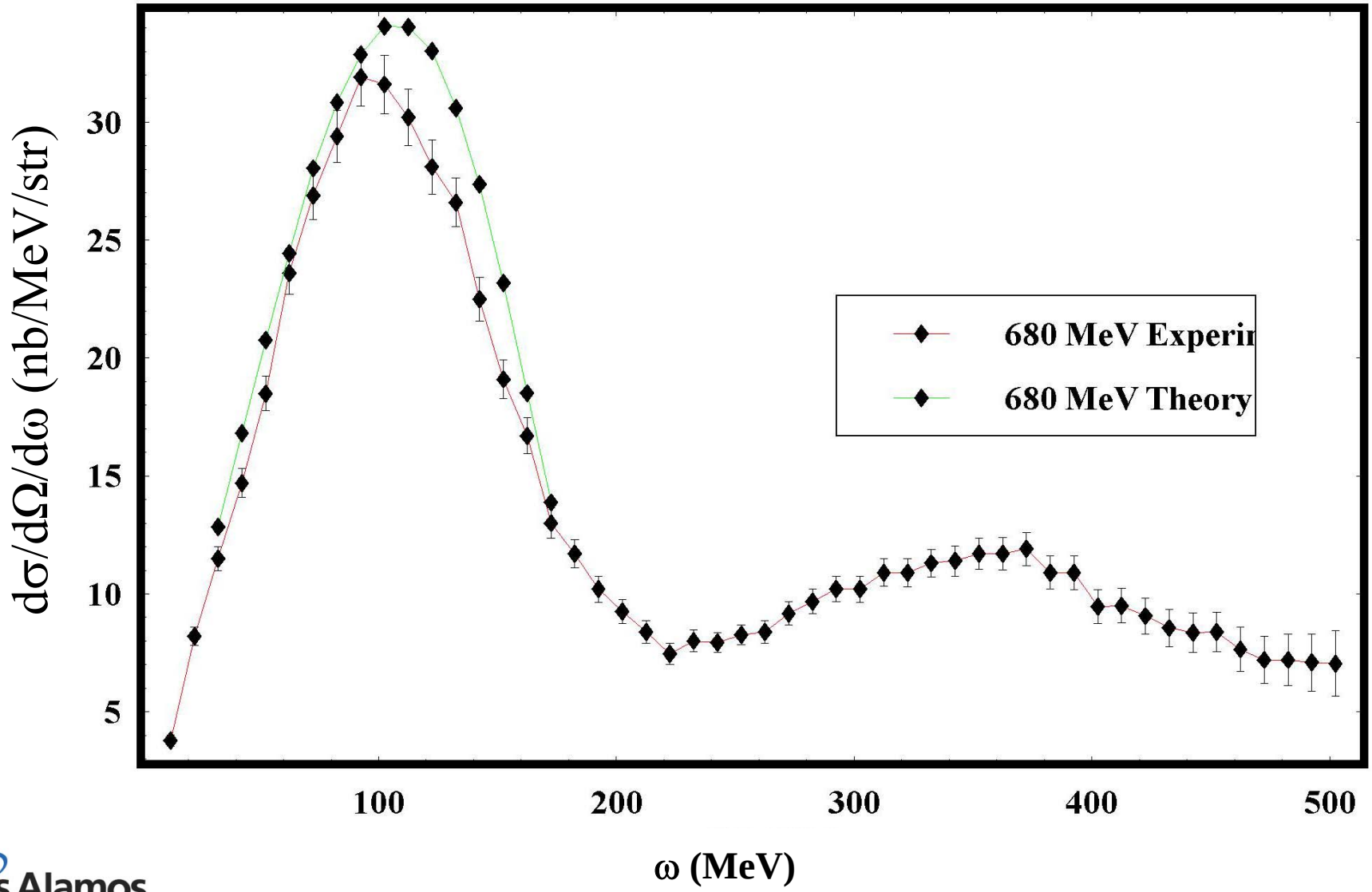
Model 1 (better)



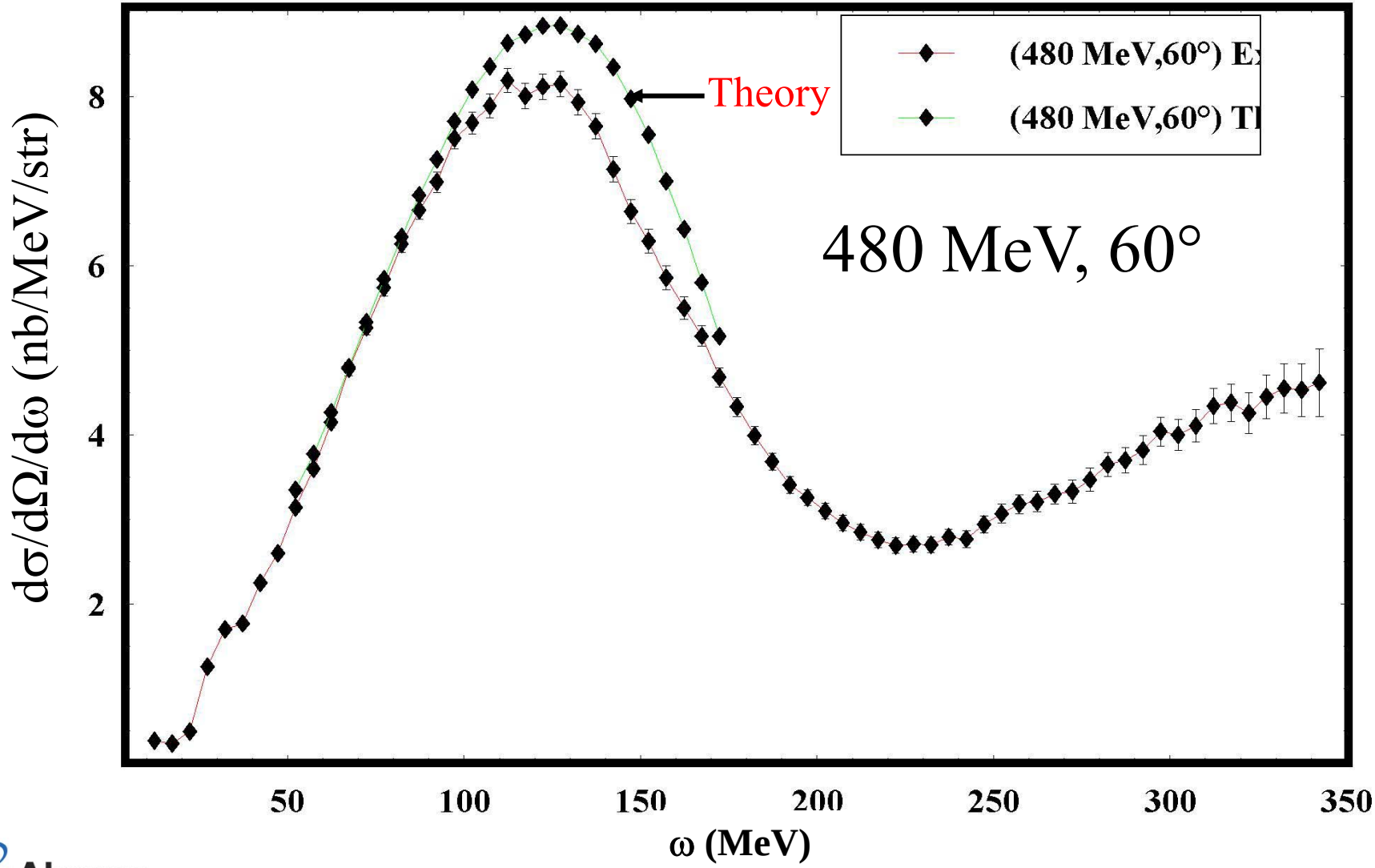
Model 2

- Harmonic oscillator momentum distribution
- Include binding energy
- ‘Realistic’ nuclear potential

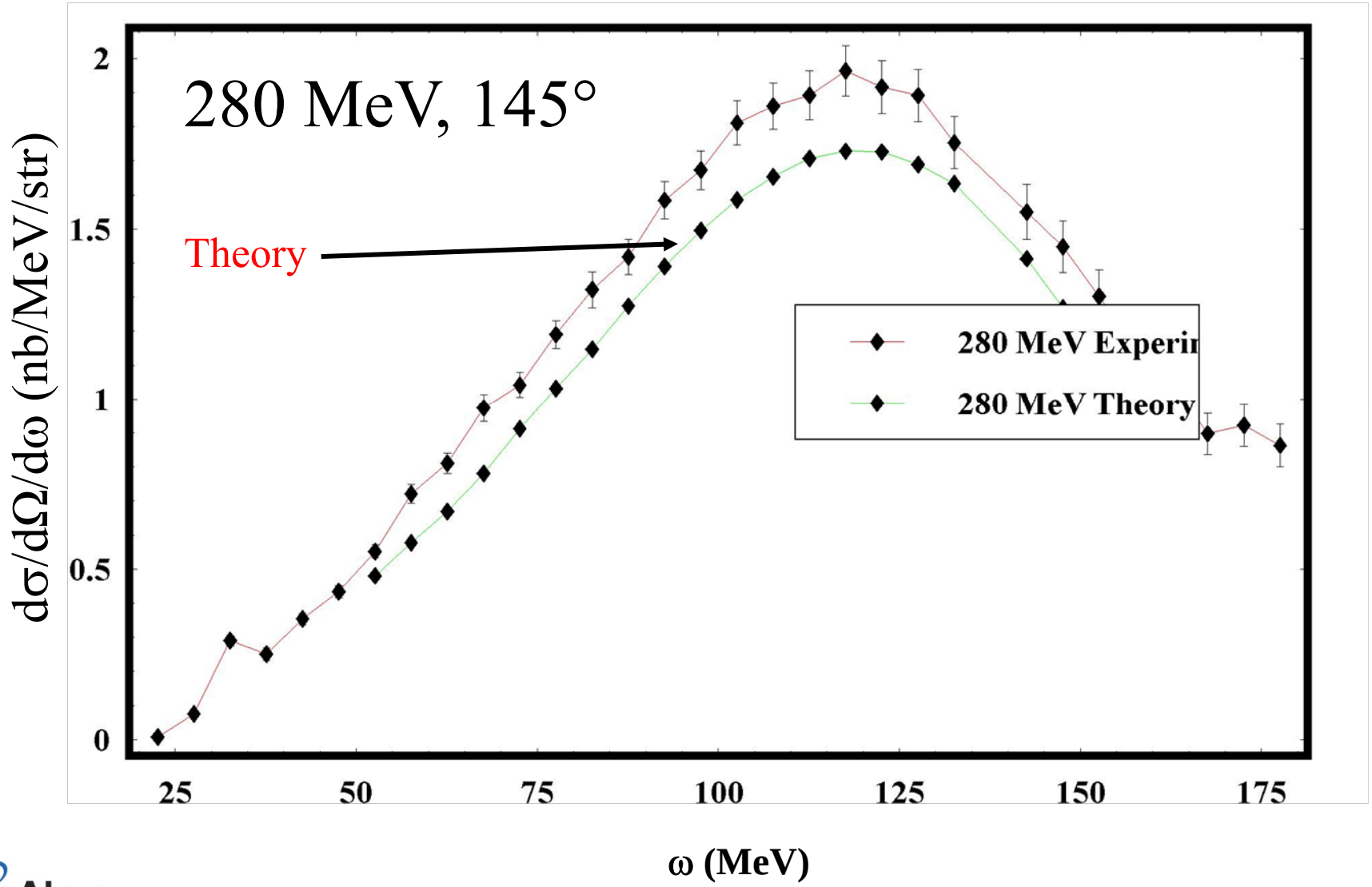
Model 2 (good)


dσ/dΩ/dω (nb/MeV/str)
30
25
20
15
10
5
100
200
300
400
500
ω (MeV)
680 MeV Experi
680 MeV Theory

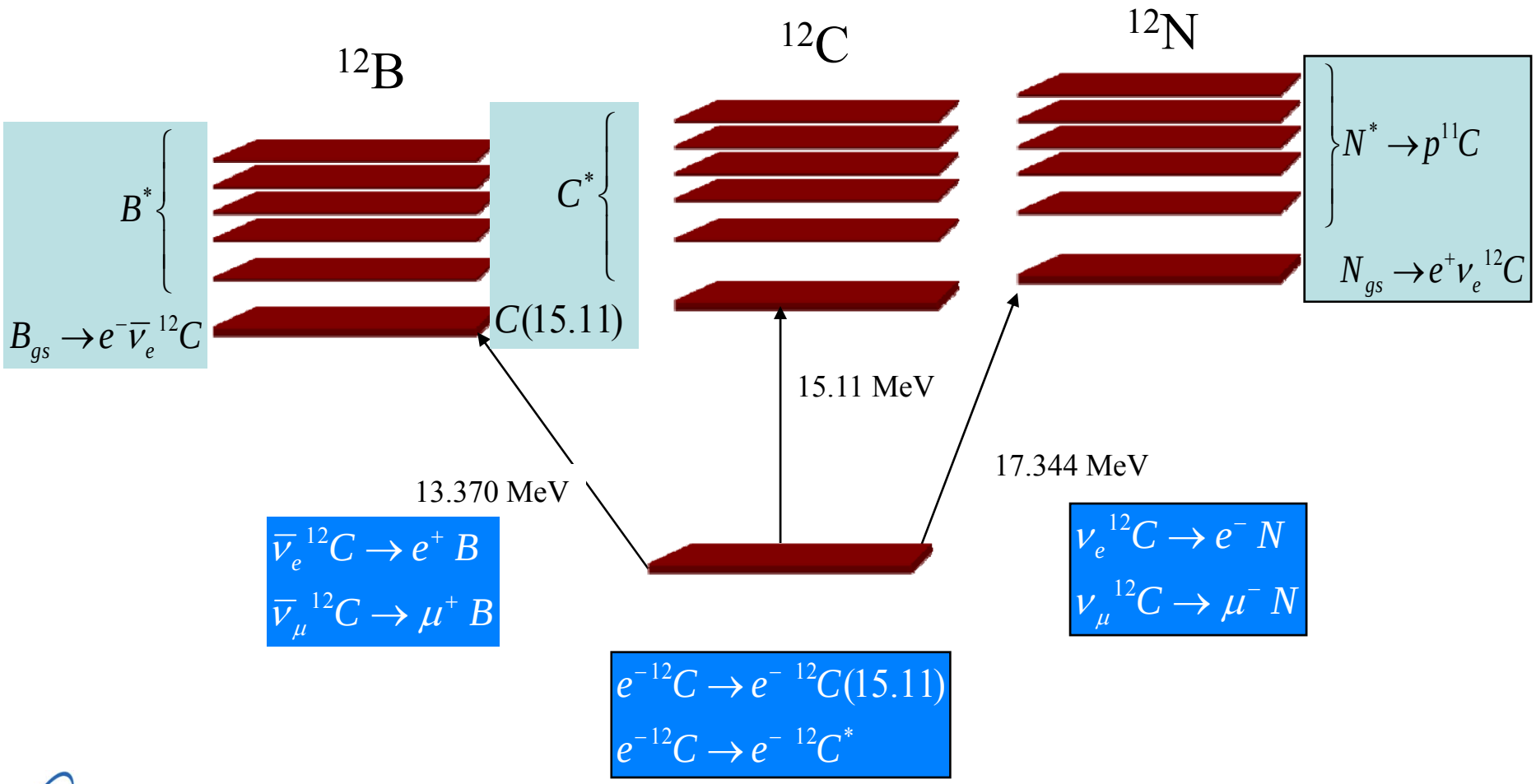
Model 2 (good)


(480 MeV,60°) E
(480 MeV,60°) Th
Theory
480 MeV, 60°
dσ/dΩ/dω (nb/MeV/str)
ω (MeV)
2
4
6
8
50
100
150
200
250
300
350

Model 2 (good)


280 MeV, 145°
Theory
280 MeV Experir
280 MeV Theory
dσ/dΩ/dω (nb/MeV/str)
ω (MeV)
0
0.5
1
1.5
2
25
50
75
100
125
150
175

Neutrino-^{12}C Interactions



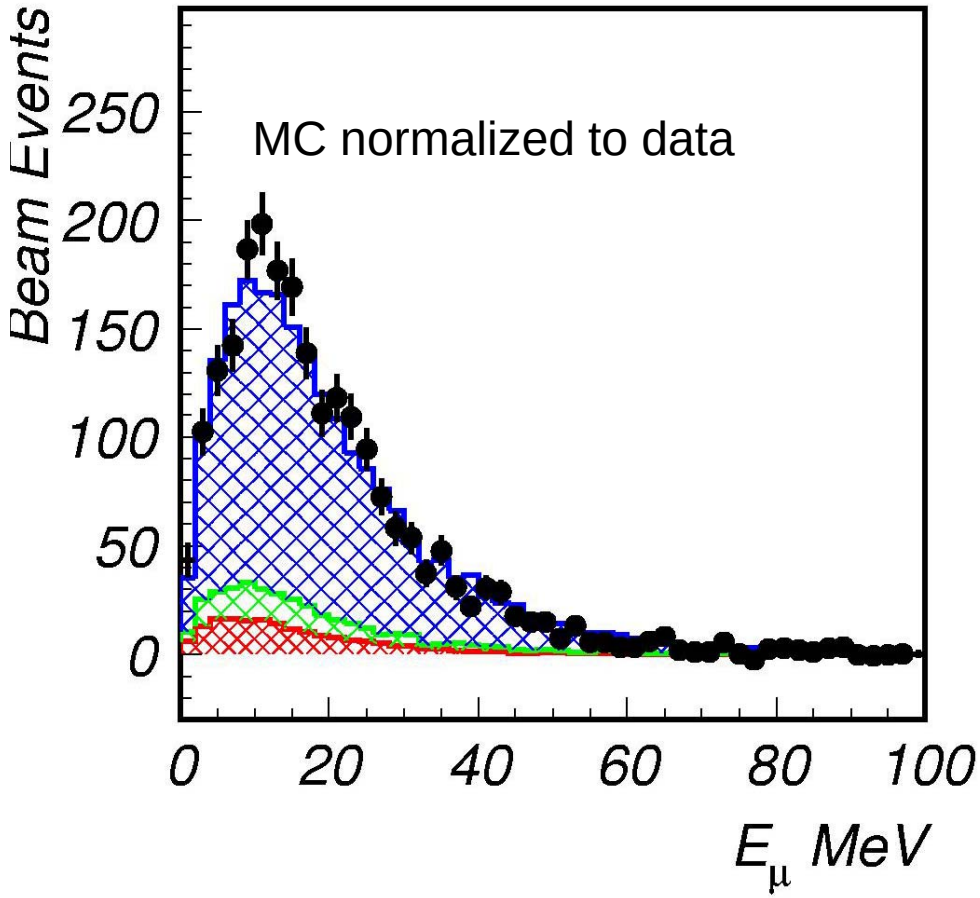
LSND Excited State ν_μ-^{12}C Events

- The only "precision" measurement of quasi elastic neutrino scattering on Carbon

$$\nu_\mu {}^{12}C \rightarrow \mu^- {}^{12}N^*$$

$$\langle \sigma \rangle_{meas} = (10.5 \pm 1.6) \times 10^{-40} cm^2$$

This is 40-50% lower than expected!



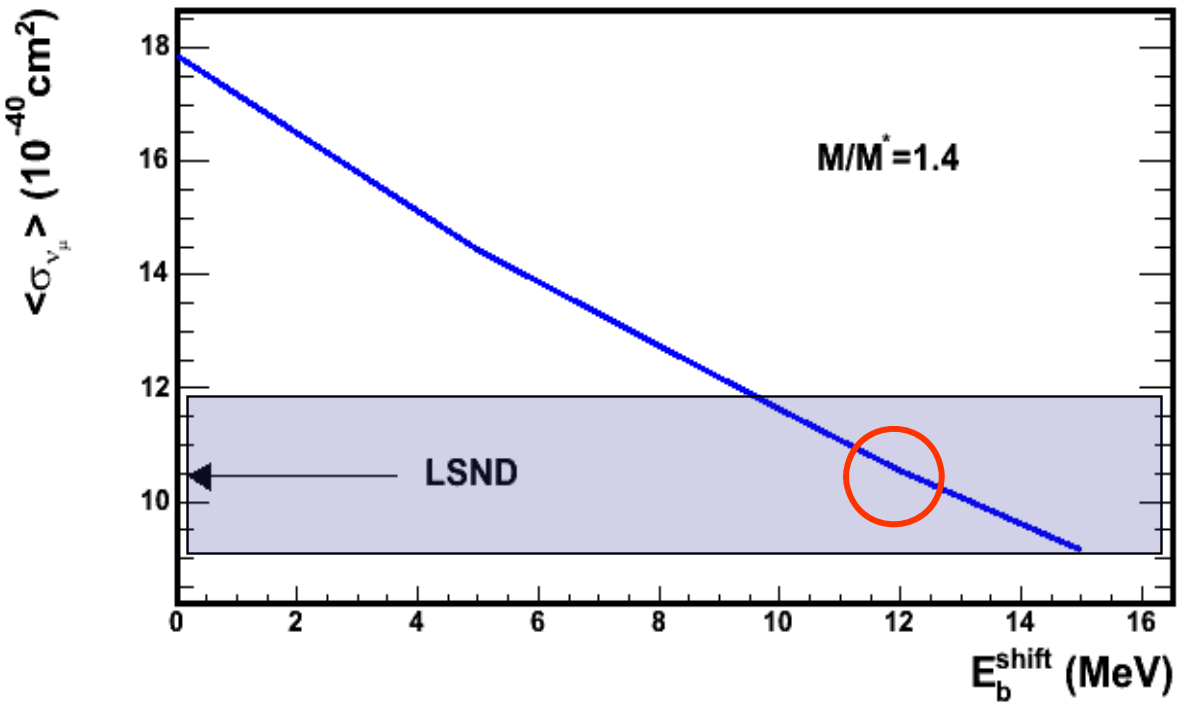
Result of “Model 2”-like calculation for LSND inclusive

Nuclear Corrections:

-effective mass of nucleon
-binding energy change

The LSND data prefers:

M/M* ~ 1.4
E_b ~ 15.11 + 12 MeV
~ 27.1 MeV
(this corresponds to 25 MeV in electron scattering)



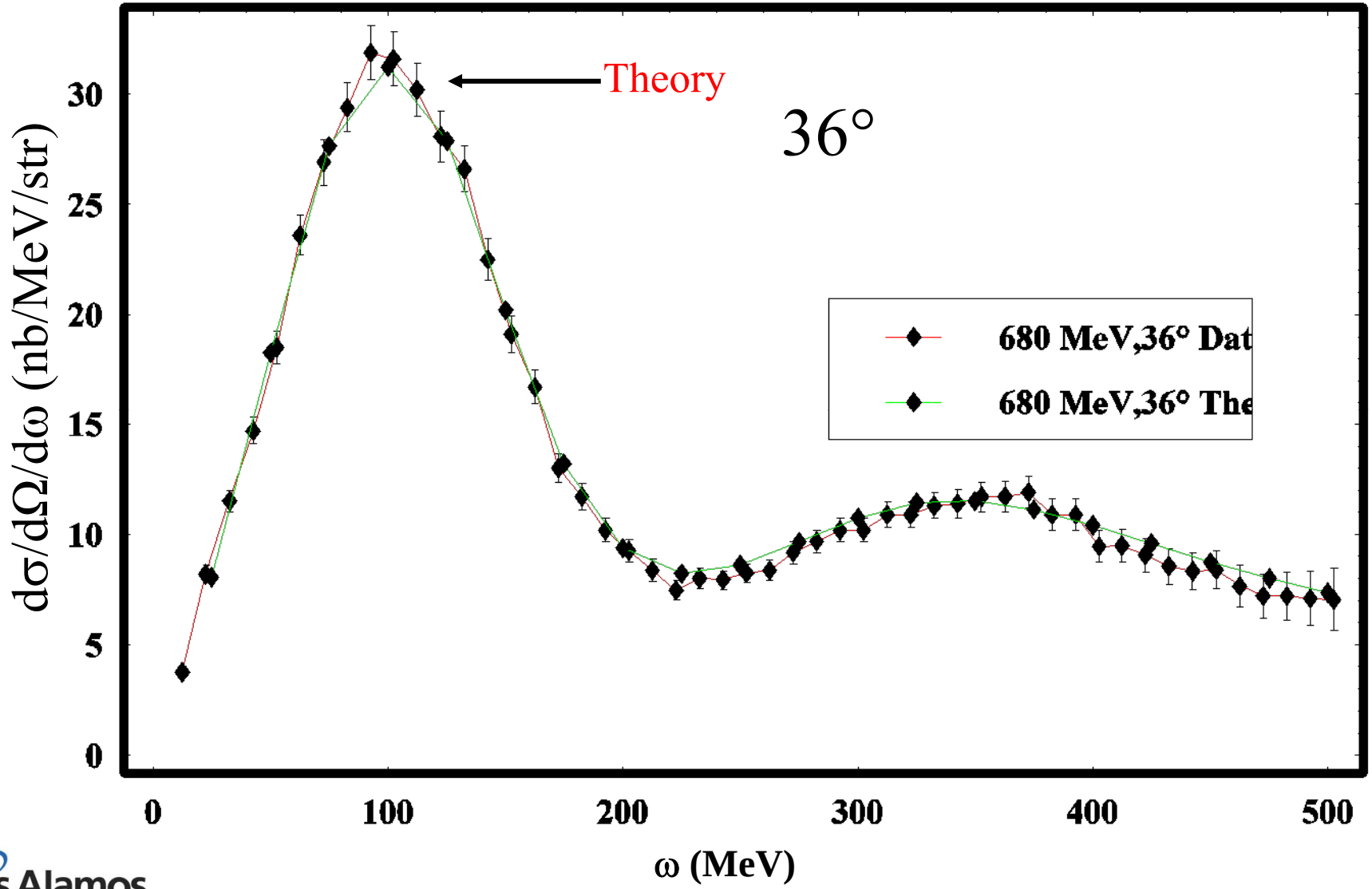
Conclusions
(quasi elastic neutrino scattering)

- “Model 2” seems to provide a “simple intuitive solution” to LSND’s cross section puzzle
- Simple nuclear effects are important for quasi elastic neutrino processes
- Provides a good anchor point for MiniBooNE…. but MiniBooNE requires cross sections up to ~1 GeV

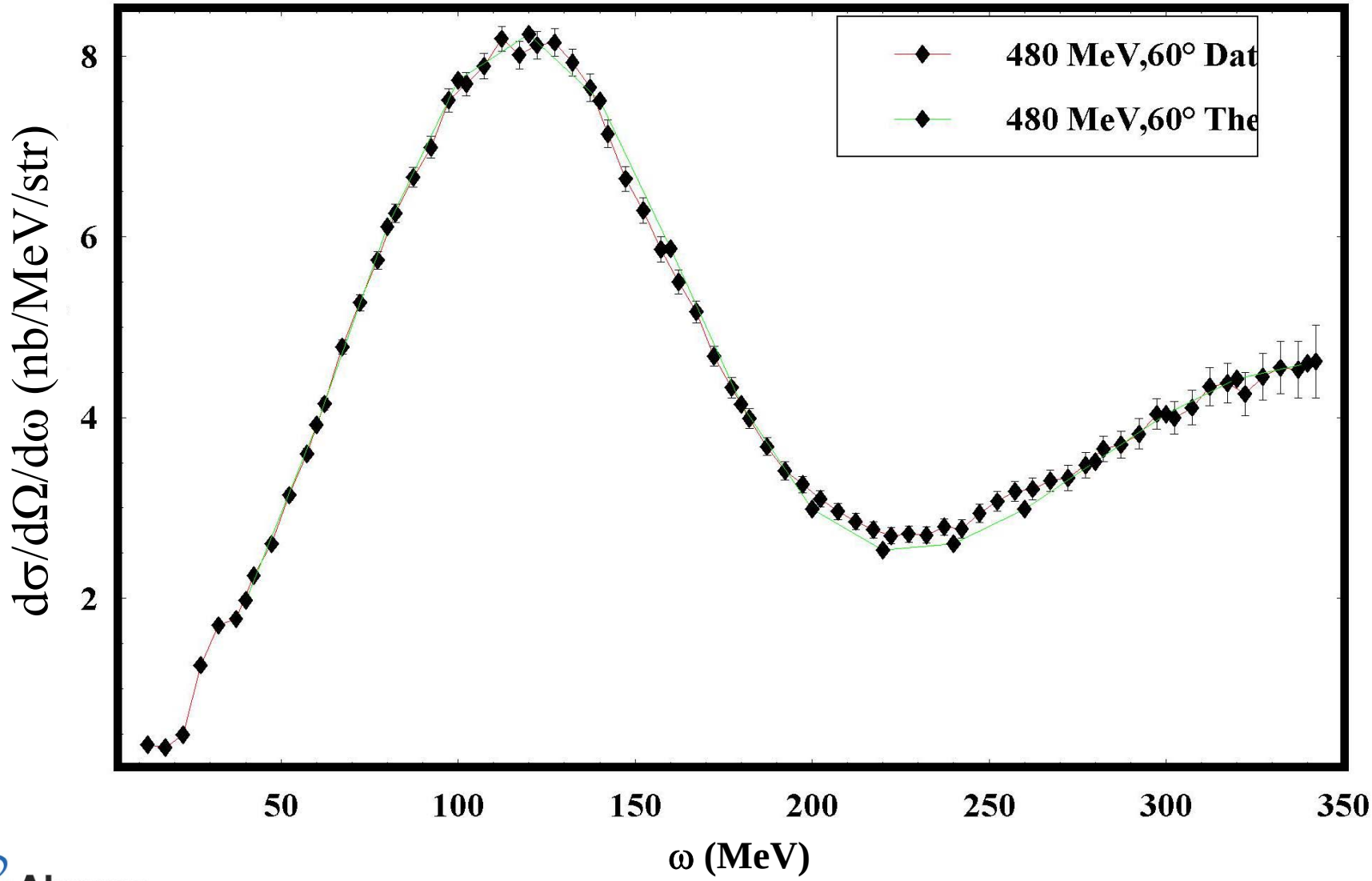
Extension to Higher Energies: Model 3

- Harmonic oscillator momentum distribution
- Include binding energy
- ‘Realistic’ nuclear potential
- Add short range correlation effects (high momentum)
- Add Delta resonance

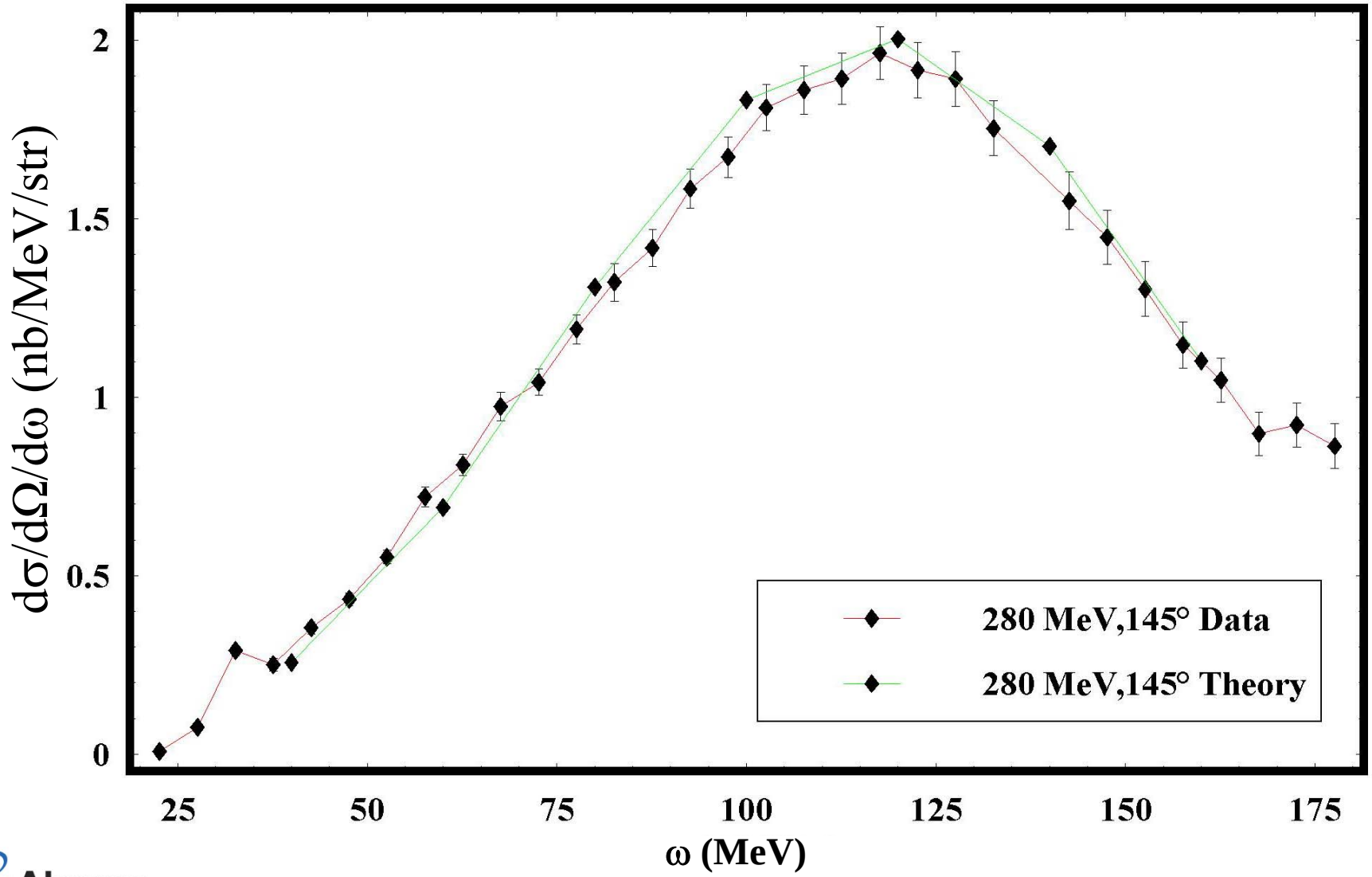
Model 3 (very good)



Model 3 (very good)



Model 3 (very good)



TBD…

- Extend Model III to neutrinos, mostly done but needs finishing touches

- Comparison with other ee’ data, other A ?

Antineutrino Running

- Good agreement with electron scattering data is not enough! Determines only the Vector part of the cross section.

- Axial part of weak current is not present in electron scattering, however the axial part can be extracted in an unambiguous way from a combination of neutrino and anti-neutrino data at MiniBooNE

Axial Part of Cross Section

$$\left(\frac{d^2\sigma}{d\Omega_2 d\epsilon_2}\right)_{\nu/\bar{\nu}} = \frac{G_F^2 cos^2\theta_c k_2^2 \cos^2(\frac{\chi}{2})}{2\pi^2 M_T}$$

$$\left\{W_2 + \left[2W_1 + \frac{m_l^2}{M_T^2}W_\alpha\right]\tan^2(\frac{\chi}{2}) + \frac{(W_\beta \pm W_8)\, m_l^2}{M_T\epsilon_2 \cos^2(\frac{\chi}{2})}\right.$$

$$\left.\mp 2\left(\frac{W_8}{M_T}\right)\tan(\frac{\chi}{2})\sec(\frac{\chi}{2})\left[q^2\cos^2(\frac{\chi}{2}) + |\mathbf{q}|^2\sin^2(\frac{\chi}{2}) + m_l^2\right]^{\frac{1}{2}}\right\}$$

Difference of neutrino and anti-neutrino cross section gives axial terms directly:

$$W_8 \sim \left(a_7(|\mathbf{q}|,\omega) + \frac{\omega}{|\mathbf{q}|}a_6(|\mathbf{q}|,\omega)\right) F_A(q^2)\left(F_1(q^2) + F_2(q^2)\right)$$

The End…